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THE UNITED KINGDOM METEOROLOGICAL OFFICE OBJECTIVE ANALYSIS SCHEME FOR GATE

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SUMMARY

The objective analysis scheme devised for the numerical forecasts that were run in near real time over the GATE area was an adaptation of the optimum interpolation method first described by Gandin. Data extraction and analysis of wind and geopotential were carried out on p-surfaces with subsequent interpolation to σ-surfaces, mutual adjustment between wind and geopotential fields being produced by use of numerical variational analysis. Humidity analyses were carried out directly in σ-coordinates. Data of all types were used, including satellite soundings and aircraft reports. The methods of error assessment for optimum interpolation are briefly described, and an account is given of the types of quality control applied to the raw data. Comparisons of some objective and subjective analyses show that the results of the techniques adopted are encouraging.

1. INTRODUCTION

Before the Tropical Research Group in the Meteorological Office were able to take the unique opportunity of the GATE experiment to use real data for testing their numerical modelling of the tropical atmosphere by comparisons with the real atmosphere, the data needed to be transformed into a form that could be handled by the prediction equations. This task was carried out by an Objective Analysis Group in the Forecasting Research Branch. The requirement was to develop an objective analysis scheme to assimilate as many different types of data as possible by means of a quasi-operational objective analysis scheme which was to be run every 12 or 24 hours, less than a day after observation time, with the 12- or 24-hour forecast providing the background field for the next analysis. The Tropical Research Group needed the surface pressure, upper-air temperatures and winds in σ-coordinates ($\sigma = p/p_*$, where p_* is the surface pressure), and humidities by layers of the σ-coordinates. The area to be covered extended from 35°N to 15°S and from 77°W to 49°E. A latitude/longitude grid was used with a spacing of 2°.

Because of the northerly latitude reached by the analysis area, and perhaps also the mid-latitude experience of the Objective Analysis Group in the Forecasting Research Branch, it was decided that a certain amount of balancing between the wind and the mass fields was desirable before the dynamical initialization process. It seemed advantageous to do this at a stage when adjustments to the two fields could take into account information concerning data density and the reliability of the analyses. This information was available because estimates of the error variance of the analyses were obtainable from the basic optimum interpolation analysis scheme that was used. The adjustment scheme used required the solution of the Balance Equation in reverse (mass field from wind field), and since our previous experience had not extended to solving this in σ-coordinates it was decided to carry out the basic analyses of mass and velocity in pressure coordinates, adjust the fields, and then interpolate into σ-coordinates. Analyses of geopotential and wind components were performed at pressure levels 1000, 950 (height only), 850, 700, 500, 400, 300, 250, 200, 150, 100 and 70 mb. It was originally intended to include the 30- and 10-mb levels but the quality and quantity of data were too poor and climatological values were used instead.

There are other reasons for including an adjustment step besides the reduction of amplitude of initial gravity waves. The basic analyses of each variable were obtained by interpolation from observations of the particular variable, using the process of optimum interpolation, which will be outlined later. The interpolation at each point required the solution of a number of simultaneous linear equations equal to the number of observations used, therefore the number of observations used to interpolate at each point needed to be limited for economy reasons. This introduced into the analyses roughnesses which needed to be removed. Also, by using some diagnostic relationship between the wind and mass variables, the adjustment process allowed values of one variable to help with the analyses of the other variable; this was important in areas where data were sparse. In particular there were often large numbers of satellite wind vectors available in areas where there were few reliable observations of geopotential, for instance, over central South America and the south-western parts of the tropical Atlantic, and here the adjustment process enabled the wind observations to influence the shape of the analysed geopotential field. In the objective analysis scheme for the 10-level model, only geopotential analyses are produced, and the wind observations influence these analyses directly through the geostrophic or gradient-wind equations.

The analysis scheme was followed by an initialization process which is described elsewhere in this issue, and the cycle of analysis, initialization and forecast can thus be summarized as follows:

(a) Derive wind and height background fields from previous forecasts which verify at time T, by interpolation from σ- to p-surfaces, except for relative humidity which was for model σ-layers.

(b) Extract data for time T.

(c) Adjust background fields in the light of the observational data, and mutually adjust the wind and geopotential fields using a variation analysis technique to give a preliminary set of analyses. After study of

data and analyses by a monitoring team, insert corrections and bogus data as required and repeat analysis for wind and geopotential fields to give final analyses.

(d) Interpolate from wind and geopotential fields and pressure surfaces to wind and temperature fields for σ-layers and surface pressure.

(e) Reduce high-frequency waves by mutual adjustment of wind and mass fields in dynamical initialization step.

(f) Use model to advance fields from time T to time $T + 12$ (or 24).

2. Data

The data used came from radiosondes from ship and land stations, satellite sounding reports (SIRS), upper winds and pilot balloons, radar, rawinsondes or LOCATE systems, aircraft reports, satellite cloud vector reports (ATS and GOES), and surface reports from ships and land stations. The data extraction programs were written by members of the Dynamical Climatology Branch and a certain amount of quality control had been done by the time the objective analysis programs were employed.

Analyses were carried out at fixed times, and data were used provided that their observation time was within three hours of the time for which the analysis was valid. No attempt was made to adjust off-time observations in any way at all except by reducing their weight (increasing their error variance) as their time discrepancy increased.

Wind reports from aircraft were used at the two nearest analysis levels, one above and one below, and were adjusted to take into account the vertical wind shear as estimated from forecast values available from the background fields. High-level and low-level ATS winds were allocated to the 250-mb and 850-mb levels respectively. SIRS data were corrected for excessive warmth, corrections varying from 20 m at 850 mb to 40 m at 500 mb and 110 m at 70 mb.

After the 100-mb and 70-mb analyses had been carried out, all radiosonde reports of geopotential at these levels were compared with the analysed fields and the differences found were interpreted as being caused by the complete sounding being systematically warm or cold. Fractional corrections were then made to the observed values at the lower levels as in the analyses for the 10-level model.

3. Error assessments for optimum interpolation

In optimum interpolation, the method used for obtaining grid-point values, each observation used and each background field value is given a weight that depends, among other things, on the reliability of the observation and of the background field. The more reliable they are, the greater their weight, so that considerable effort went into the assessment of the variance of the errors both of the observations and of the background field. Values used were assessed from the literature, but it is important to note that the error variances required by the optimum-interpolation process are not solely dependent on instrumental errors but have to include the effects of scales of motion which are too small to be represented on the grid used; this is termed 'noise' and the optimum interpolation scheme assumes that this noise has no spatial correlation. For each

wind component a noise value of 9 $m^2 s^{-2}$ was added to the estimated instrumental variances (Alaka and Elvander, 1972). For values of geopotential obtained from radiosondes, values were taken from Rutherford (1972). The net effect of noise is to reduce the weight of the observations. The assessment of errors of background fields was problematical because none of these forecasts had ever been run on real data, so that estimates had to be made from our experience with the 10-level model and from statistical studies of the temporal variation of meteorological fields in the tropics.

4. Data checking

All the data had undergone quality-control checks before the objective analysis programs were reached, but a further check was introduced before data were used in the analysis. An interpolated value was obtained at the observation point using the background field and observations other than the one in question. The observation of a variable was rejected if the difference between the observed value and the interpolated value was greater than a quantity which itself depended on the reliability of the interpolated value. The criterion was based on the theory of Maximum Likelihood. In areas of plentiful observations the interpolated value will be fairly reliable and therefore a small departure from this on the part of the observation is sufficient reason for its rejection. On the other hand, in an area of few observations the interpolated value itself is unreliable and a large difference may be due to the unreliable analysis, and therefore one should accept observations in this area more readily. The process for accepting or rejecting observations is a most important part of any objective analysis scheme. One of the fundamental problems of objective analysis—or for subjective analysis for that matter—is the decision whether or not to reject a particular observation which deviates markedly from a forecast background field; it is difficult to decide whether it is a very bad observation, or one of the most valuable observations because it indicates that the background field is very badly in error.

In spite of these checks a considerable amount of human monitoring was required to correct erroneous reports, or to insert artificial ones where this was thought desirable. Considerable difficulty was encountered over the mountainous regions of East Africa, over South America, and the south-western parts of the tropical Atlantic and round the boundary of the analysis area. In general, analyses were not amended subjectively unless they contained features that were obviously unrealistic.

5. Analysis technique

The analysis of relative humidity was obtained using the scheme described by Atkins (1974). This is based on Cressman's successive-approximation method in that it uses a weighting function which depends on the distance of the observation from the grid point, but a major difference is that the weighting function is anisotropic in that it also depends on the gradient of the background field, i.e. on the 12- or 24-hour forecast. The weighting function falls off more rapidly in directions across the contour lines of the background field than in directions along the contour lines. This helps to preserve the patterns existing in the background fields and was found to be very advantageous in mid latitudes.

The analysis process for the geopotential and winds is in two stages. First

there is horizontal interpolation to obtain values of geopotential and wind independently at each grid point, and this is followed by the 'adjustment stage', which allows the two fields to influence each other.

For the first stage, the method of optimum interpolation was used. Optimum interpolation was first described by Gandin in 1963 but it has undergone a number of developments and a recent description has been given by Kruger (1969).

As with most objective analysis methods, optimum interpolation combines the observations with a first-guess field which provides an analysis value in areas where there are no observations but which becomes less important (i.e. has less weight) in areas where observations are more numerous. The observations are used to correct the first guess. The difference between each observation and the background field at the observation point gives us an estimate of the error of the background field at this observation point. If we have a number of observations near to, and preferably surrounding, a particular grid point then we can combine these error estimates to form a correction to the background field at the grid point; this is the process of interpolation. Obviously if the observation point is close to the grid point it provides a more reliable correction to the grid-point value and therefore deserves more weight than an observation further away. The rate at which the weight should fall off with distance depends on the spatial coherence of the background error field; if the error field is 'spotty', so that the error at one point is not correlated with the error a grid length or two away, then the weight falls off more rapidly than if the errors are on a fairly broad scale. Knowledge of the characteristics of the error fields both in their magnitude and in their scale is important in many analysis schemes and is certainly very important for optimum interpolation.

The weight given to an observation depends also on a number of other factors. For instance, reliable observations get more weight than unreliable observations and because of this we need to have estimates of the variances of the errors of each type of observation. Also observations get more weight if the background field is thought to be unreliable.

In optimum interpolation the weights given to the observations (or rather the weight given to the estimates that they provide of the error of a background field) also depend on one other factor—how close observations are to other observations. Obviously if one is using, say, four observations to interpolate a value at a grid point it is better that the observations should surround the grid point rather than cluster all together on one side of the grid point. Optimum interpolation allows the weights to take into account the presence of other observations.

The mathematics is complex, but optimum interpolation allows us to calculate the weights, taking all the above into consideration, which, in a statistical sense, provide the best (optimum) estimate of the grid-point value from the given distribution of observations and the assumed reliability of the background field. Once the weights are determined it is possible to estimate statistically the variance of the error of the analysis at the given grid point.

The observations are used essentially to provide estimates of the errors of the background field, so that it can be corrected. Information on the spatial interrelationship of these errors has to be provided in the form of spatial correlation functions of the errors. If many forecasts had been available, these

functions could have been calculated empirically. However, since no forecasts had in fact been carried out, the functions were given the form

$$R(r) = \frac{1 - r^2/2\lambda}{(1 - r^2/\lambda)^{5/2}},$$

where $R(r)$ equals the value of the correlation function for given r, r = distance between observations or between observation and grid point, and λ = a constant which determines how broad or how narrow the curve is. The shapes of the curves are similar to those given by Atkins (1970) and resemble a 'cocked hat'. λ was chosen so that $R(r) = 0$ at 2000 km; this gives a broader function than is really true for fields in the tropics, particularly for the wind field, and results in a smoothing of the analyses. This seemed desirable in view of a lack of experience at that time.

The number of observations used for estimating the value at each grid point was kept to 8; several experiments had shown that raising the number to 12 made very little difference to the interpolated values and thus did not warrant the doubling of the work involved. In fact if there are several observations close to the grid point it is likely that a smaller number still would suffice. Where possible the 'nearest' two observations in each quadrant about the grid point were chosen, where the 'distance' was given by

$$\frac{R(i,g)}{1 + \dfrac{\sigma^2 \text{ errors of observation}}{\sigma^2 \text{ errors of background}}},$$

where $R(i,g)$ is the value of the correlation function between the observation point and the grid point, and the σ^2 are the variances of the errors of observation and of the errors of the background field. This allows a good-quality observation to be selected even though it is somewhat further away from the grid point than another observation which is less reliable.

6. Adjustment stage

Up to this point the analyses of geopotential and wind are independent of each other, apart from the fact that the background fields of both are derived from the forecasts from the prediction model. It is known that in middle latitudes, it is desirable, when use is made of the primitive equations, for the initial wind and geopotential fields to be related to each other in such a way that the forecasts start smoothly. This relationship is described mathematically by the Balance Equation, and it can be shown that if this equation is satisfied along with one or two other conditions, then there will be no generation of spurious gravity waves, which show up as rapid variations of surface pressure in the first few hours of the forecast. The procedure used for the 10-level model is to analyse the geopotential field (with the aid of the wind observations as interpreted by the geostrophic and gradient-wind approximation) and then to use the Balance Equation to derive a suitable wind field from the geopotential field. Now since the Balance Equation is rather like the geostrophic-wind equation with additional terms representing the effects of curvature and diffluence, as in the gradient-wind equation, the winds derived from the Balance Equation become unrealistic as one approaches the equator. However, it is

quite possible, and in fact it is easier, to obtain a geopotential field from the wind field in low latitudes using the Balance Equation and use is made of this fact.

The adjustment used is based on the numerical variational analysis due to Sasaki (1970) using a form of his 'weak constraint' in his 'timewise localized' form. First of all a geopotential field h_B is obtained from the analysed wind field, $\mathbf{V}^I$, by solving the Balance Equation in reverse, the effects of friction being allowed for at 1000 mb. Using a mathematical technique called the Calculus of Variations, we then find fields of geopotential and wind (called the adjusted fields) which are similar to the analysed fields but are nearer to a balanced state than the original fields. The process is described in more detail in the Appendix. An important feature is that in areas where one or other of the fields is estimated to be reliable, it is little changed, but where one analysed field is estimated to be rather unreliable compared with the other it will undergo greater adjustment.

Some comparisons of velocity and geopotential fields before and after the variational step show that the two fields are modified in a reasonable way. Since the solution of the Reverse Balance Equation is very smooth in low latitudes the net effect is a smoothing of small-scale features in the geopotential field unless they correspond to features in the wind field. Further away from the equator smoothing is still present but the two fields interact in a more positive way.

7. Complete scheme

The process described so far is applied independently at each analysis level in the atmosphere. Figure 1 shows the outline of the complete scheme. The first level analysed is 1000 mb—this is required to provide a reference level for the SIRS data. Next follow the 70-mb and 100-mb analyses, each followed by radiosonde corrections in the same manner as for the 10-level model (Atkins, 1970). Analyses at 850, 500 and 250 mb are then made simultaneously and the results of these levels are used to adjust the background fields of geopotential and winds at all the remaining levels, thus ensuring a degree of vertical consistency; this also reduces the number of levels at which bogus data need to be inserted when the intervention team decide that analyses require amending.

8. Some results

The remaining diagrams show comparisons of wind data, objective analyses and subjective analyses, the latter being made in Dakar during the GATE period. They are shown for 12 GMT, 2 September 1974 for 1000 mb. The objective and subjective analyses show good agreement, but details of the smaller-scale features such as convergence lines and centres differ. The subjective analyses are neater and more consistent in these areas than the objective analyses, but nevertheless the latter are reasonably consistent with the existing observations.

9. Summary and comment

There is undoubtedly much room for improvement. In particular more attention should be paid to the vertical structure and hence to the temperature and

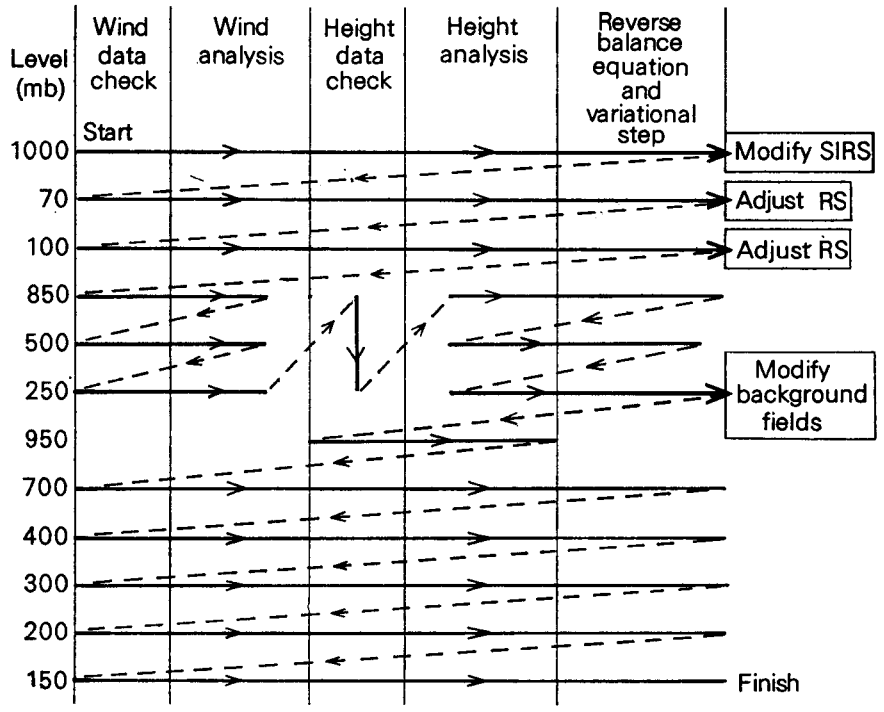

FIGURE 1—GATE ANALYSIS—OUTLINE

RS = radiosonde; SIRS = Satellite Infra-red Spectrometer Sounding.

stability fields. It would also be better if the analysis were done in σ-coordinates since the interpolation to and from the pressure-coordinates system gives rise to considerable roughnesses in the fields presented to the time integration, particularly near mountainous regions.

Analysis of meteorological charts in tropical regions is normally a highly subjective process. Most hand-drawn analyses are limited to representation of flow patterns by streamlines and isotachs, and consistency in time is difficult to achieve. Investigations by the Tropical Research Group in the Meteorological Office show that in these analyses and forecasts there are trough lines which keep a reasonable progression and consistency over a period of several days, and this is very encouraging.

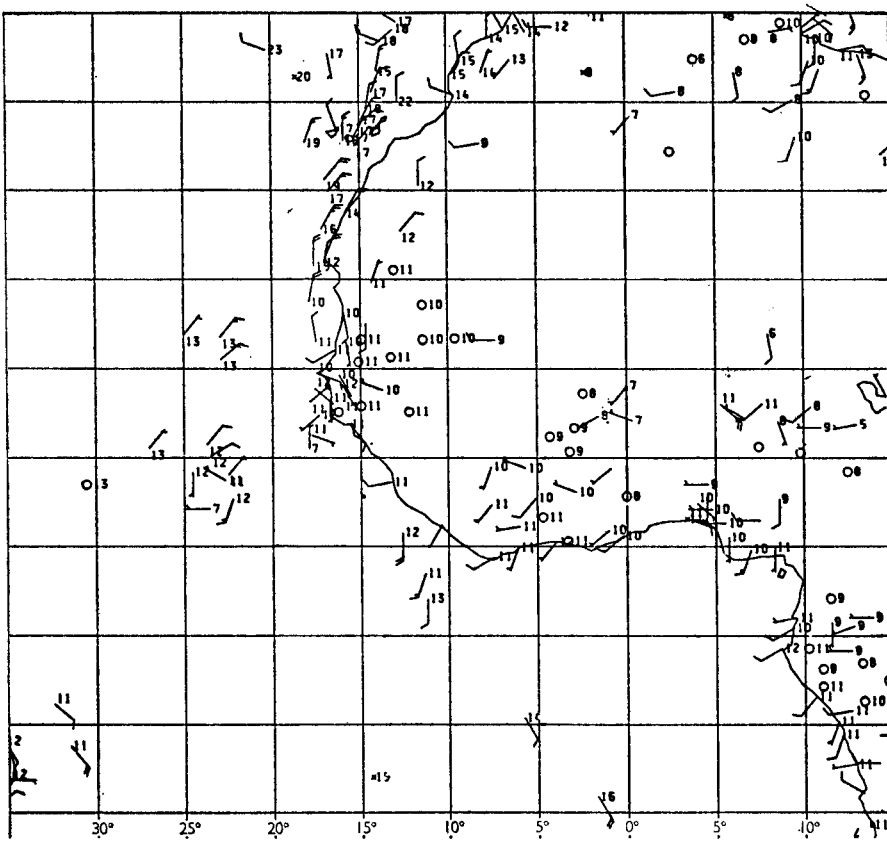

FIGURE 2—DATA FOR 1000 mb AT 12 GMT ON 2 SEPTEMBER 1974

1000-mb heights in metres. Each full feather denotes 5 m/s.

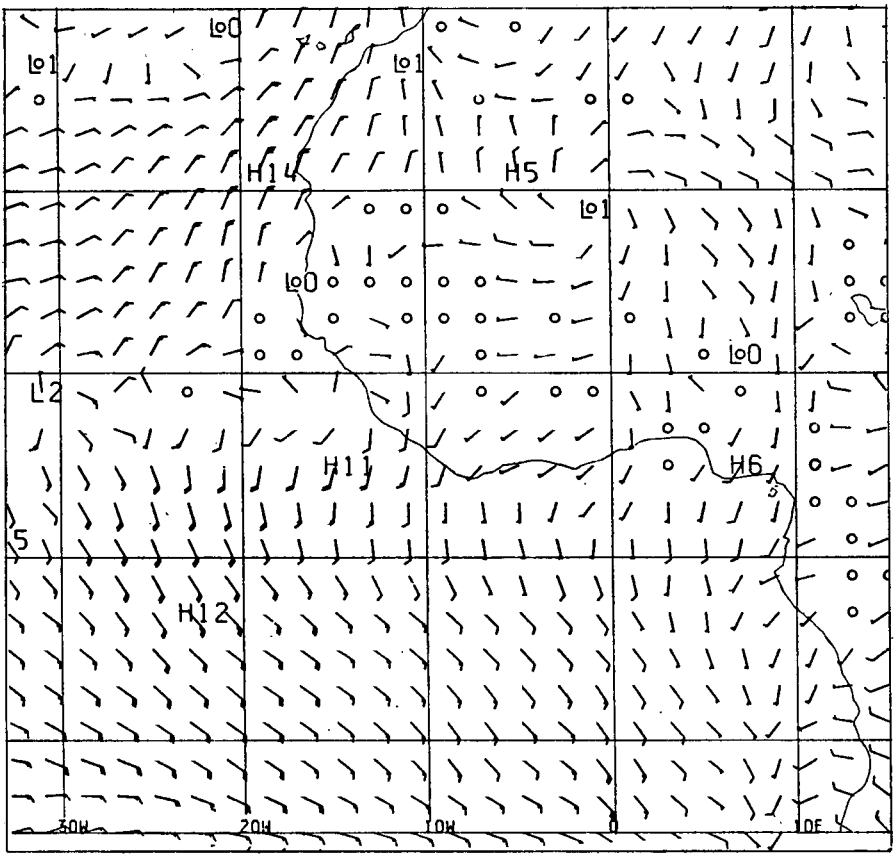

FIGURE 3—PART OF OBJECTIVE ANALYSIS OF WIND FIELD AT 1000 mb AT 12 GMT ON 2 SEPTEMBER 1974

Each full feather denotes 5 m/s.

REFERENCES

ALAKA, M. A. and ELVANDER, R. C.	1972	Optimum interpolation from observations of mixed quality. *Mon Weath Rev*, **100**, pp. 612–624.
ATKINS, MARGARET J.	1970	Objective analysis of upper air height and humidity data on a fine mesh. *Met Mag*, **99**, pp. 98–110.
	1974	The objective analysis of relative humidity. *Tellus*, **26**, pp. 663–671.
GANDIN, L. S.	1963	Objective analysis of the meteorological fields. Leningrad, Gidrometeoizdat.
KRUGER, H. B.	1969	General and special approaches to the problem of objective analysis of meteorological variables. *Q J R Met Soc*, **95**, pp. 21–39.
RUTHERFORD, I. D.	1972	Data assimilation by statistical interpolation of forecast error fields. *J Atmos Sci*, **29**, pp. 809–815.
SASAKI, Y.	1970	Some basic formalisms in numerical variational analysis. *Mon Weath Rev*, **98**, pp. 875–883.

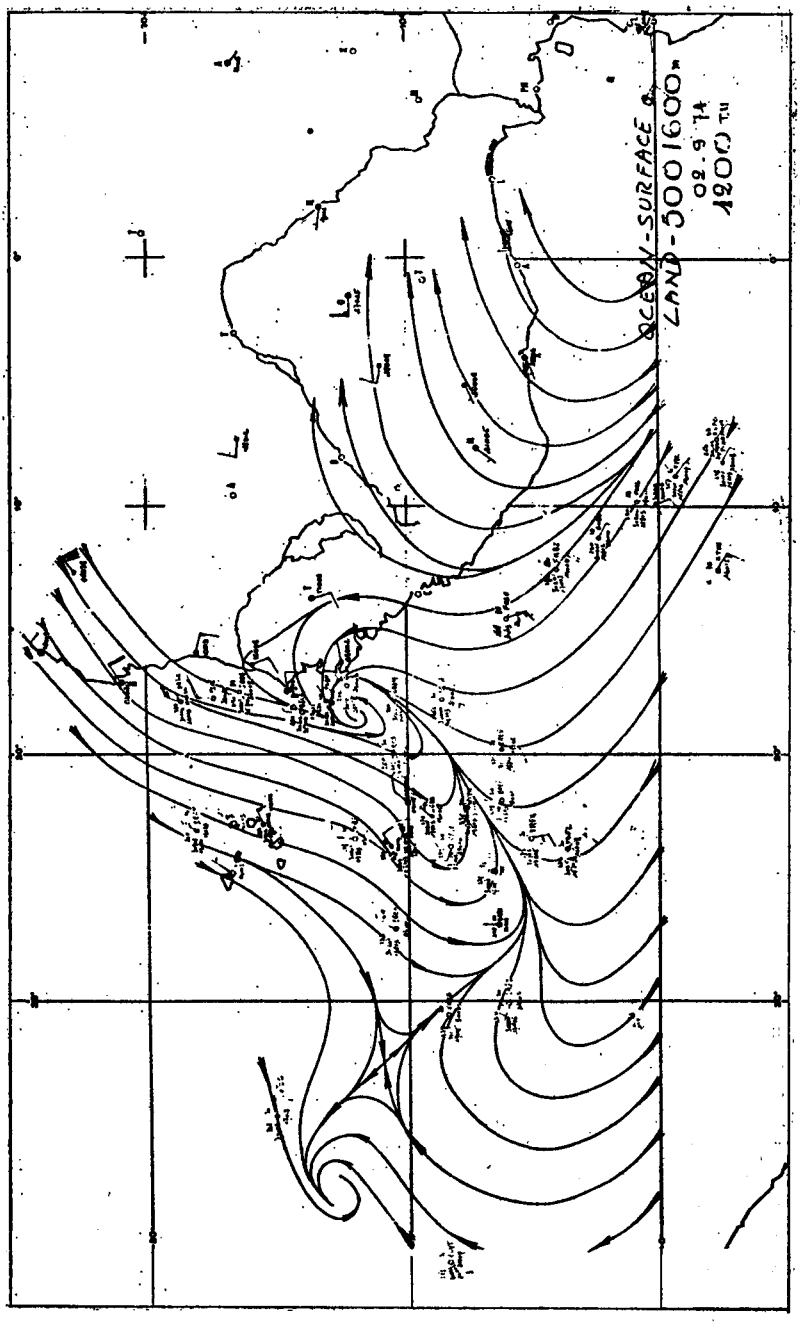

FIGURE 4—SUBJECTIVELY ANALYSED STREAM FUNCTION AT 12 GMT ON 2 SEPTEMBER 1974

Surface wind over ocean, 500–600-m wind over land.

APPENDIX—THE SASAKI ADJUSTMENT STEP

First of all a geopotential field h_B is obtained from the analysed wind field, $\mathbf{V}^I$, by solving the Balance Equation in reverse. The following integral is then required to be minimized, where the integration is taken over the whole area:

$$I = \iint [\alpha(\mathbf{V} - \mathbf{V}^I)^2 + \beta(h - h^I)^2 + \lambda' \{g\nabla(h - h_B) + f\mathbf{k}\wedge(\mathbf{V} - \mathbf{V}^I)\}^2]dxdy,$$

where $\mathbf{V}$ = final (adjusted) value of the velocity field,
h = final (adjusted) value of the geopotential field,
h^I = (initial) analysed value of the geopotential field, and
$\mathbf{k}$ = unit vertical vector.

The minimization required is with respect to variations of $\mathbf{V}$ and h; the parameters α, β and λ' are determined before the integral is minimized. The first two terms keep the departures from the analysed fields to a minimum. Bearing in mind the fact that h_B and $\mathbf{V}^I$ satisfy the Balance Equation, the third term requires that the departures of $\mathbf{V}$ and h from the Balance Equation solution should be approximately in geostrophic balance; because the weak constraint form is used, the geostrophic balance is not actually enforced, and the extent to which the constraint is satisfied depends on the size of λ' relative to α and β. Note that near the equator the term $\mathbf{V} - \mathbf{V}^I$ will be negligible; thus $\mathbf{V}$ will be very close to $\mathbf{V}^I$; the absolute value of h will be close to h^I, but the shape (gradients) of h will be close to h_B.

The variational analysis is straightforward and we are required to solve the following elliptic equation:

$$\nabla \cdot (r\nabla h) - \beta h = \nabla \cdot (r\nabla h_B) - \beta h^I,$$

where $r = \dfrac{\lambda' g^2 \alpha}{\alpha + \lambda' f^2}$.

Suitable boundary conditions are obtained by setting $h - h^I = 0$ round the edge.

The weights α and β are taken as being inversely proportional to the estimated variance of the error of the relevant analysis at each particular point. These parameters therefore vary over the grid and where either of the analyses is regarded as reliable it will not be changed by very much; where one of the analyses is regarded as being unreliable it will tend to be altered to make the constraint more closely satisfied. The values of α and β were of course obtained from the optimum interpolation process. λ' was taken as a constant and a fairly small value was chosen so that fields were not modified except where the error variances indicated that they were particularly unreliable. When the modified values of the geopotential field have been obtained the new values of the velocity field are obtained from the expression

$$\mathbf{V} - \mathbf{V}^I = \frac{\lambda' g}{\alpha + \lambda' f^2} f\mathbf{k}\wedge\nabla(h - h_B).$$

Note that when f is small, $\mathbf{V}$ is virtually independent of the correction to the geopotential field. When λ' is large the relationship reduces to a geostrophic relationship between $\mathbf{V} - \mathbf{V}^I$ and $h - h_B$.

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NUMERICAL MODELLING USING GATE DATA

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SUMMARY

During GATE an 11-layer primitive-equation model was run in near real time to produce forecasts for up to 24 hours ahead. The flow and rainfall patterns were forecast fairly well apart from a tendency to develop spurious small-scale features. There is a discussion of the possible causes of these and of some systematic errors in the predicted vertical structure of the atmosphere.

INTRODUCTION

The Meteorological Office Tropical Modelling Group was set up at about the beginning of 1973 to develop improved techniques for simulating the tropical atmosphere in the Dynamical Climatology Branch's general-circulation models. Formation of the Group at this time allowed it to take advantage of the data obtained during GATE in summer 1974. A limited-area version of the global model then being developed in the Branch was constructed centred on the GATE B-scale area so that forecasts could be made for up to three days without serious contamination of the B-scale area forecast by boundary effects. Forecasts from analyses based on GATE data could then be made with different versions of the model and the quality of the simulations so obtained could be assessed by comparing them with reality.

Creation of satisfactory initial analyses required suitable data-extraction, analysis and forecast programs similar to those used in operational numerical forecasting but adapted to the tropics. To develop such a system, to gain experience of its behaviour and to meet the need for a large number of initial cases from which to select initial and verification analyses, it was decided to run a near-real-time analysis/forecast cycle throughout each of the three phases of GATE using all data available at Bracknell about 24 hours after observation time. The analysis system is described in the paper in this issue by D. E. Jones.

THE FORECASTING MODEL

As indicated above, the model used was a limited-area version of the 11-layer global primitive-equation model recently developed in the Dynamical Climatology Branch. The vertical coordinate is $\sigma \equiv p/p_*$ where p is pressure and p_* is pressure at the earth's surface. The boundaries and nominal central levels of layers are specified in Table I.

TABLE I—LAYER BOUNDARIES AND NOMINAL LEVELS IN σ-COORDINATES

Layer	11	10	9	8	7	6	5	4	3	2	1
Boundaries	1	0·975	0·9	0·79	0·65	0·51	0·37	0·27	0·195	0·125	0·06	0
Nominal level	0·9874	0·9370	0·8438	0·7177	0·5772	0·4363	0·3174	0·2305	0·1574	0·0886	0·0221	

* *Note:* This paper is based on an unpublished report by the quoted authors with some abridgement and further explanations by the Editor.

The vertical resolution was chosen after consideration of representation of the boundary layer, extratropical fronts and jet streams, inflow and outflow of tropical convective systems, and the stratosphere.

In the horizontal, variables were represented on a 2° latitude–longitude mesh with boundary rows along 35°N, 15°S, 77°W and 49°E. The finite-difference scheme was similar to that described by Corby *et alii* (1972), though with modifications in the vertical differencing to maintain energy conservation in the sense discussed by these authors and with time-averaging at every time-step to avoid 'splitting' between alternate forecast fields. Lateral boundary conditions were of the 'sponge' type described by Kesel and Winninghoff (1972). Instead of the non-linear diffusion term described by Corby *et alii* (1972) a filter of the type described by Shapiro (1971) and Francis (1975) was used every six hours to eliminate very short waves from the fields of sea-level pressure, horizontal wind, specific humidity and temperature. The boundary-layer and surface fluxes of heat, moisture and momentum were calculated from the model variables in the lowest three layers and from surface temperature by use of Method I of Clarke (1970). Evaporation was related to potential evaporation and soil moisture in a way similar to that of Manabe (1969), but fixed values of soil moisture were used with a smooth transition over Africa from moist equatorial to dry desert regions. The modelling of convection and large-scale rainfall was similar to that used by Corby *et alii* (1972). A simple radiation scheme was adopted which, however, included diurnal variation of solar heating and climatological values of albedo, specific humidity and cloudiness.

Dynamic initialization

If data obtained from analyses of the fields of wind and geopotential are used as initial data for a primitive-equation model without specific measures to adapt one to the other, high-frequency gravity waves of large amplitude are set up which bear no relation to any meteorological phenomenon and can damage or even obscure the forecast. This is because the wind and pressure fields are not 'balanced' so leading to unrealistic initial accelerations. Harmonization of the fields must be brought about artificially before they can be used to provide realistic forecasts. Various methods of obtaining suitable fields, by what are termed 'initialization procedures', have been proposed. The one applied to GATE data, known as 'dynamic initialization' was due to Nitta (1969). In this the model equations are applied iteratively to damp out the spurious high-frequency modes implied by the analyses.

As both pressure-to-wind and wind-to-pressure adjustments are to be expected among the various vertical modes and horizontal scales of a multi-level model, all the variables were allowed to adjust mutually except that the moisture field was held fixed and all sources and sinks of energy (including latent-heat release) were ignored. This last restriction is rather unsatisfactory—in particular, the balance at low levels should be influenced by friction—but no method has yet successfully incorporated source and sink terms into this type of initialization scheme. One extra effect was, however, introduced: at the end of each cycle a convective adjustment was applied to the temperature fields to prevent the generation of vertical instability.

Tests of the dynamic initialization process showed that external gravity waves implied in the analysed data were successfully removed by applying the

scheme for the equivalent of six hours of model time; indeed two to three hours might well have been enough. Comparison of forecasts made with initialized and uninitialized data showed that surprisingly little damage was done by the presence of spurious gravity waves, at least on a 12- to 24-hour time-scale, although forecasts using initialized data were smoother; rainfall was little affected. The element of balance introduced during the objective analysis may be partly responsible for this.

Forecast procedure

The forecast-analysis cycle was run with 12-hourly updating during Phases I and II of GATE (analyses at 00 and 12 GMT), and with 24-hourly updating during Phase III (analyses at 12 GMT). The change to 24-hourly updating allowed more detailed assessments of the quality of the data and analysis, and of the need for bogus data; it also allowed testing of the forecast over a longer period with less computer usage.

The procedure at time t may be summarized as follows:

(a) A previous forecast provides values of variables on σ-surfaces. Derive values at standard pressure levels by interpolation to provide background fields for analysing new observations made at time t. (This does not apply to relative humidity, which is analysed for σ-layers directly.)

(b) Extract data for time t.

(c) Carry out preliminary analysis. Insert corrections and bogus data as necessary and carry out final analysis.

(d) Interpolate from pressure surfaces to σ-surfaces.

(e) Initialize wind and pressure fields.

(f) Use model equations to advance fields from time t to $t + 12$ or $t + 24$ hours.

The data extracted in step (b) comprised surface and upper-air observations (rawinsonde, radiosonde and pilot balloon) from land stations and ships, aircraft observations of wind and temperature, estimates of wind from satellite cloud photographs, and temperature soundings from satellite radiometers. Numerous difficulties were encountered at first, but most problems had been satisfactorily solved by the time Phase III began.

Results and discussion

Attention will be confined in this section to results of the forecasts carried out during Phase III because these forecasts were made for periods of 24 hours and because data, analysis and modelling had all been improved in the light of the experience gained during the earlier phases.

The large-scale synoptic situation over the area generally varied little during the phase: the Atlantic was dominated by the north and south Atlantic sub-tropical highs with maximum heights in the forecast area of about 24 and 16 dam respectively, while between them a trough with minimum height of about 11 dam linked the continental lows over North Africa and South America. An interesting feature was a simultaneous weakening of northern high and oceanic trough from 8 to 11 September with extremes of only 18–20 dam and

13 dam. In the middle and lower troposphere, troughs moved westwards in the general easterly flow over West Africa and the northern tropical Atlantic. Figures 1 and 2 show 'analysed' and predicted trough movement at $\sigma = 0{\cdot}844$ and 500 mb (where 'analysed' here means 'objectively analysed and initialized') and also positions for 850 mb subjectively estimated from observations at

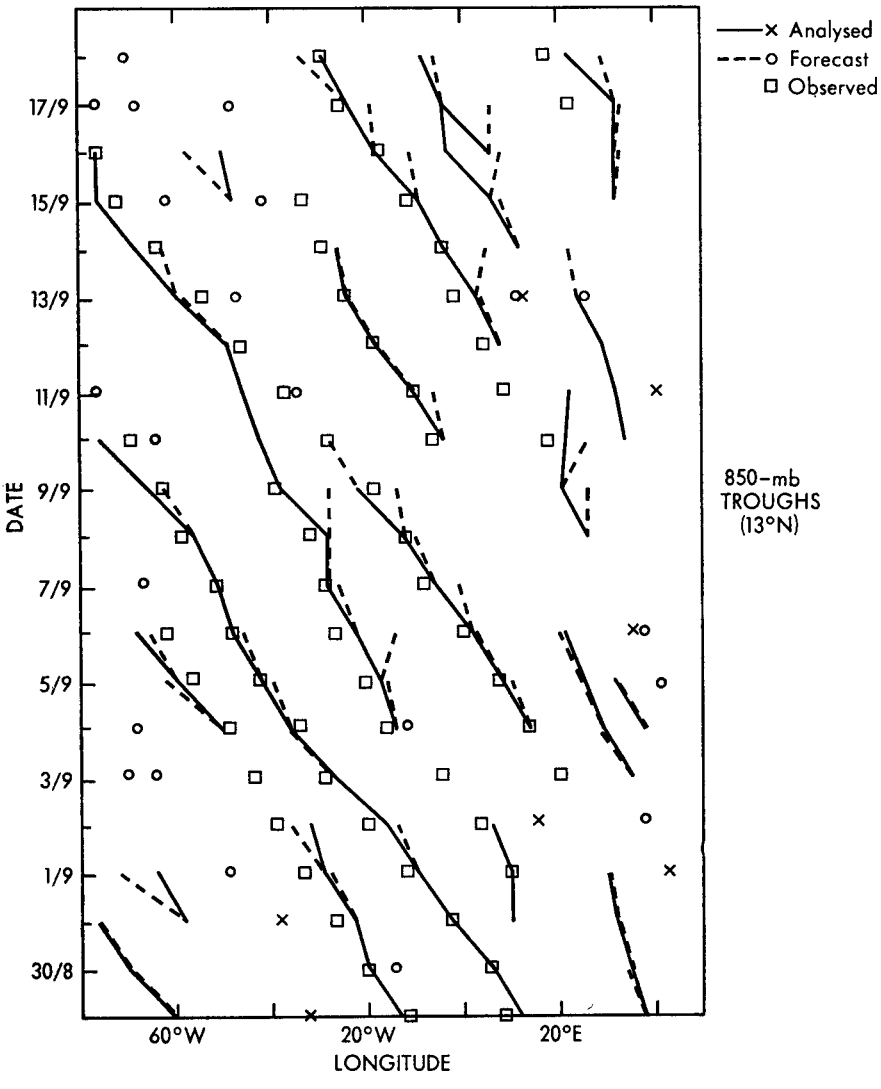

FIGURE 1—TROUGH POSITIONS AT $\sigma = 0{\cdot}844$, 13°N DURING PHASE III OF GATE

x —— analysed positions
o -- predicted positions
Squares mark subjectively estimated 850-mb trough positions.

00 GMT, and occasionally 06 and 18 GMT as well as 12 GMT; where data were inadequate for these subjective estimates, use was made of continuity and cloud information from satellites.

The errors of prediction are summarized in Table II.

The errors at level 9 are large for waves starting over land (20°W–20°E) but

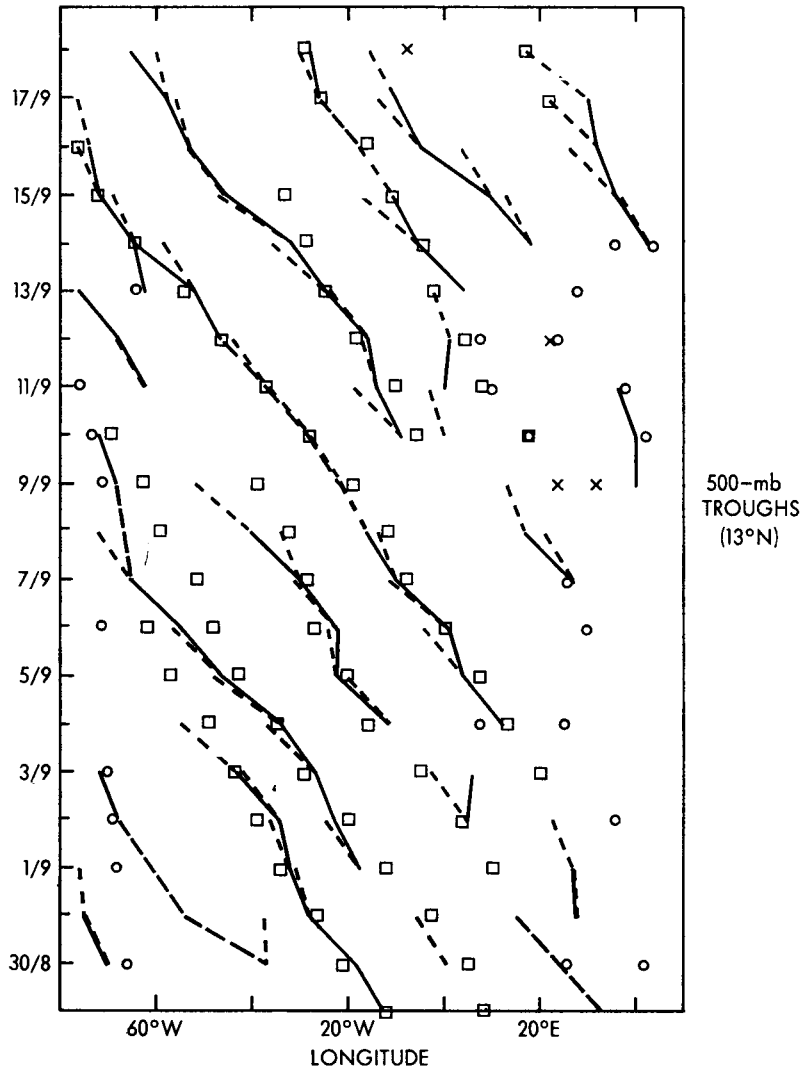

FIGURE 2—TROUGH POSITIONS AT 500 mb, 13°N DURING PHASE III OF GATE

x —— analysed positions
o – – predicted positions
Squares mark subjectively estimated 850-mb trough positions.

are much smaller over the ocean, suggesting that surface and boundary-layer friction and surface heating may have contributed to the error. Errors are much smaller at 500 mb and no longer depend on longitude, probably because of the relatively small effects of convergence and divergence at this level.

TABLE II—MEAN ANALYSED AND PREDICTED 24-HOUR WESTWARD SHIFT OF TROUGHS AND DERIVED ERROR (DEGREES OF LONGITUDE) DURING PHASE III

	60°W–20°W	20°W–20°E
$\sigma = 0{\cdot}844$ (level 9)		
Number of cases	15	18
Analysed motion	6·3°	6·3°
Forecast motion	5·3°	2·1°
Error	−1·0°	−4·2°
500 millibars		
Number of cases	20	16
Analysed motion	6·9°	6·5°
Forecast motion	7·1°	7·4°
Error	+0·2°	+0·9°

The quality of the rainfall forecasts may be judged on the broad scale from Figure 3 which shows isohyets drawn from observed and forecast totals for the period from 4 to 14 September. The observed distribution was calculated from 06 GMT observations and the forecast from the totals for the 24 hours to 12 GMT; the area from 5°N to 20°N and from 10°E to 20°W was divided into 5° squares, the 24-hour totals (observed and forecast) were meaned for each square and the isohyets were drawn on the basis of these areal mean totals.

Most of the observed and forecast rain occurred in the strip from 5°N to 10°N, and Figure 4 shows the distribution with respect to longitude and time of the 24-hour rainfall totals in this strip, both observed and forecast. The figure shows that the model successfully produced the alternation of wet and dry periods together with roughly correct longitudes for the rainfall maxima. Each wet period was associated with a westward-moving wave or trough; somewhat similar relationships were observed using larger samples of data by Carlson (1969) and Burpee (1974). (It is of interest that the wave of 5–8 September developed into hurricane 'Fifi' which devastated Honduras a few days later.)

On the fine scale, large spurious amounts of rain were forecast at a few grid points, particularly over central Africa. One reason for this was the occurrence of spurious thickness maxima produced by faulty analysis in regions where data were sparse; these spurious maxima tended to generate intense vortical disturbances. The method of parameterizing convection may also have contributed since improved results were subsequently obtained with a new 'parameterization' scheme.

An important measure of the quality of any numerical forecasting method is the degree to which it systematically reproduces the mean structure of the real atmosphere. Discrepancies between forecast and actual mean structures also provide good clues to deficiencies in parameterization and computational method which would cause major faults in longer 'climatic' simulations.

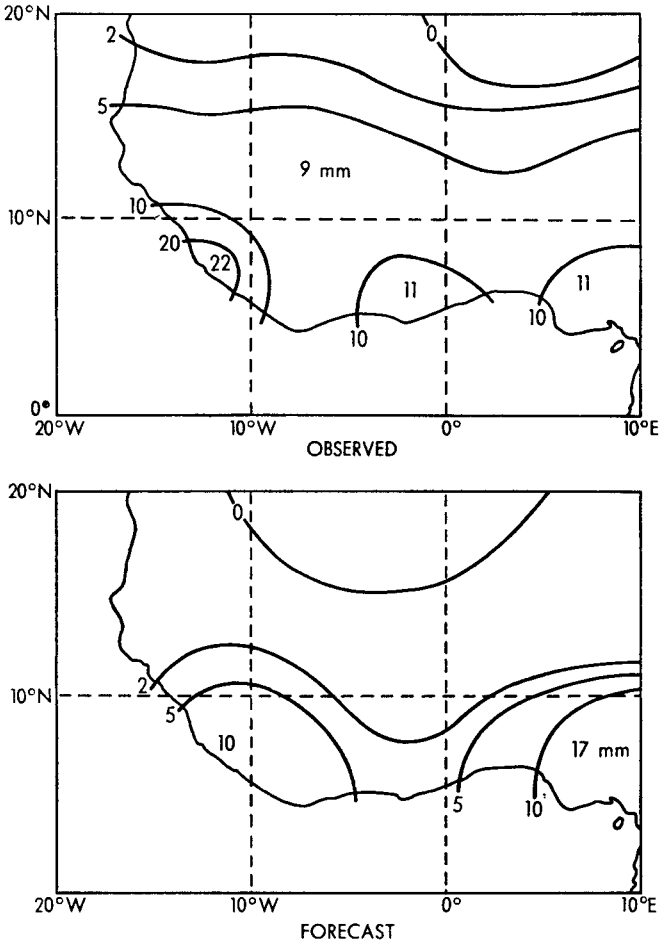

FIGURE 3—MEAN 24-HOUR RAINFALL TOTALS FOR THE 10-DAY PERIOD 4–14 SEPTEMBER 1974

Examples are presented here of the average forecast 24-hour change in the thermal structure of the atmosphere as illustrated by mean vertical cross-sections along certain longitudes. Time-mean fields were constructed by taking a mean of the initial conditions for 9–14 September and a mean of the 24-hour forecast fields verifying on 10–15 September. To show the structure of the temperature fields more clearly, temperatures were expressed as differences from those in a typical model atmosphere meaned along 7°N.

Figures 5 and 6 show the vertical cross-sections of the forecast temperature changes along 23°W and 3°E. The most noticeable feature, common to both, is the warming that takes place in the lowest layer during the forecast. Over desert regions, north of 13°N at 3°E surface temperatures increase by about 5 K during the forecast; this is probably due to the simplified treatment of radiation and soil-moisture content.

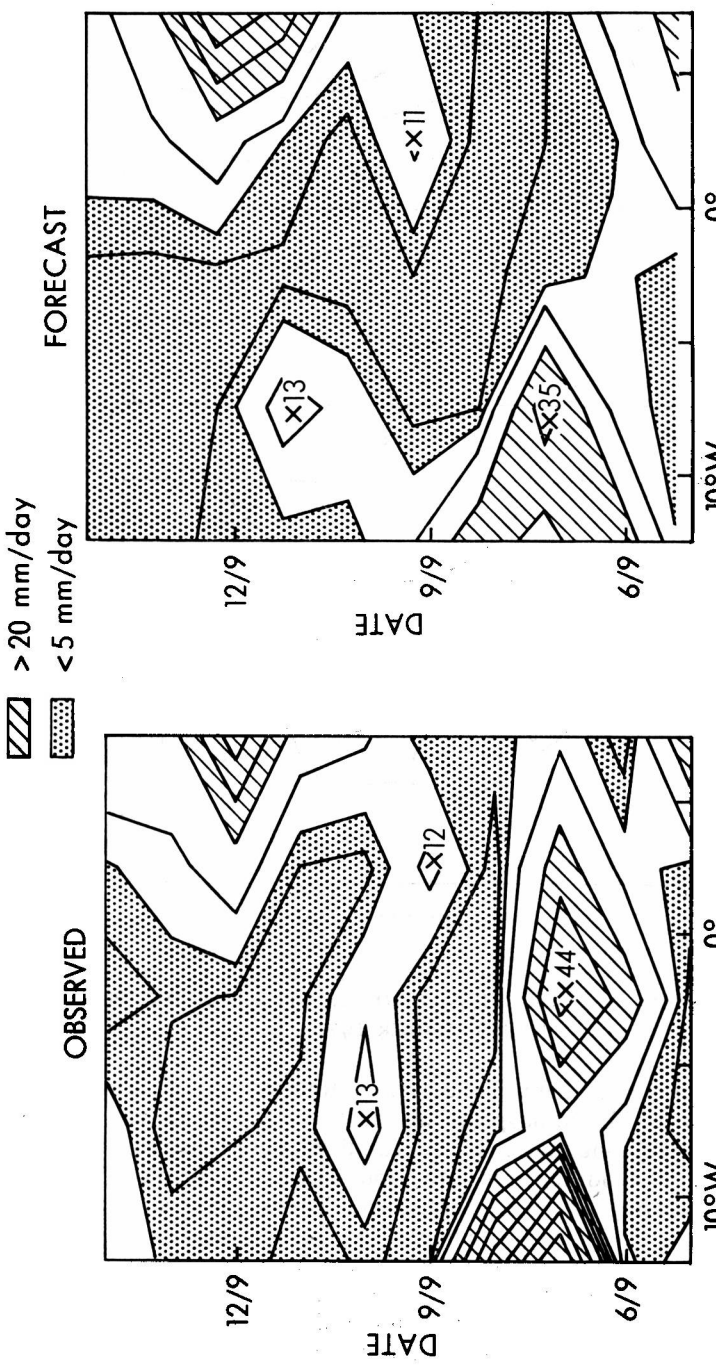

FIGURE 4—MEAN TOTALS OF OBSERVED AND FORECAST RAINFALL FOR PREVIOUS 24 HOURS

Rainfall totals are expressed in millimetres. Isopleths are at 2, 5, 10, 20, . . . 80 mm/day.

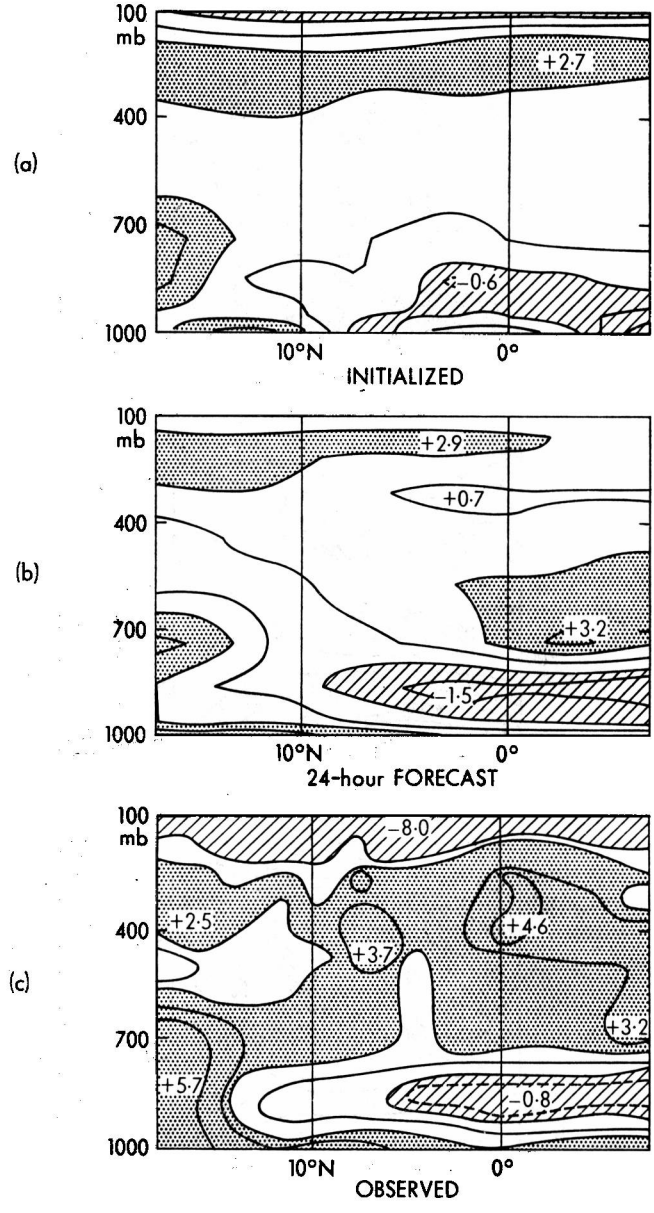

FIGURE 5—VERTICAL CROSS-SECTIONS OF TEMPERATURES IN KELVINS ALONG 23°W

Time averages for 9–14 September 1974 at 12 GMT expressed as departures from model's 7°N mean. Isopleth interval 1 K; values >2 K stippled, <0 K hatched.
(a) Initialized (9th–14th); (b) Forecast (10th–15th); (c) Observed (9th–14th).

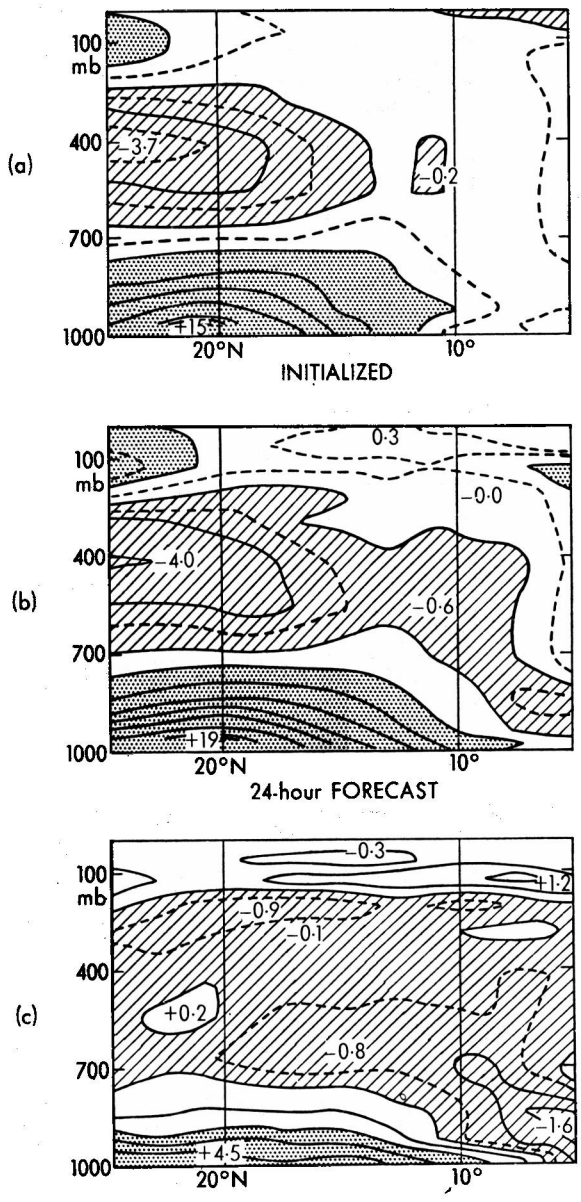

FIGURE 6—VERTICAL CROSS-SECTIONS OF TEMPERATURES IN KELVINS ALONG 3°E

As Figure 5, except that isopleth interval is generally 2 K in (a) and (b).
(a) Initialized; (b) Forecast; (c) Forecast minus Initialized.

To face page 270

PLATE I—THE ENTRANCE TO THE GATE OPERATIONS CONTROL CENTRE (GOCC) IN DAKAR

C.C.O.E. is derived from 'Centre de Contrôle des Opérations de l'ETGA'.

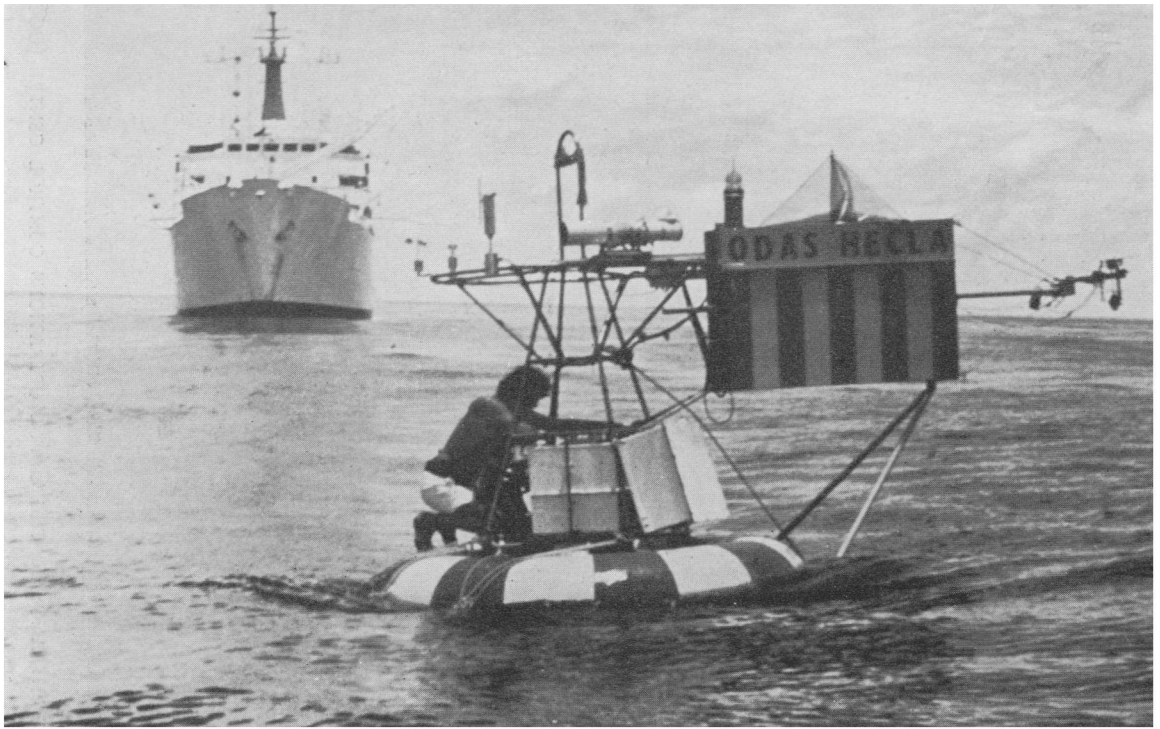

PLATE II—MAINTENANCE DURING NEARLY CALM CONDITIONS OF THE METEOROLOGICAL BUOY LAUNCHED FROM H.M.S. *Hecla*
The *Hecla* is in the background (see page 275).

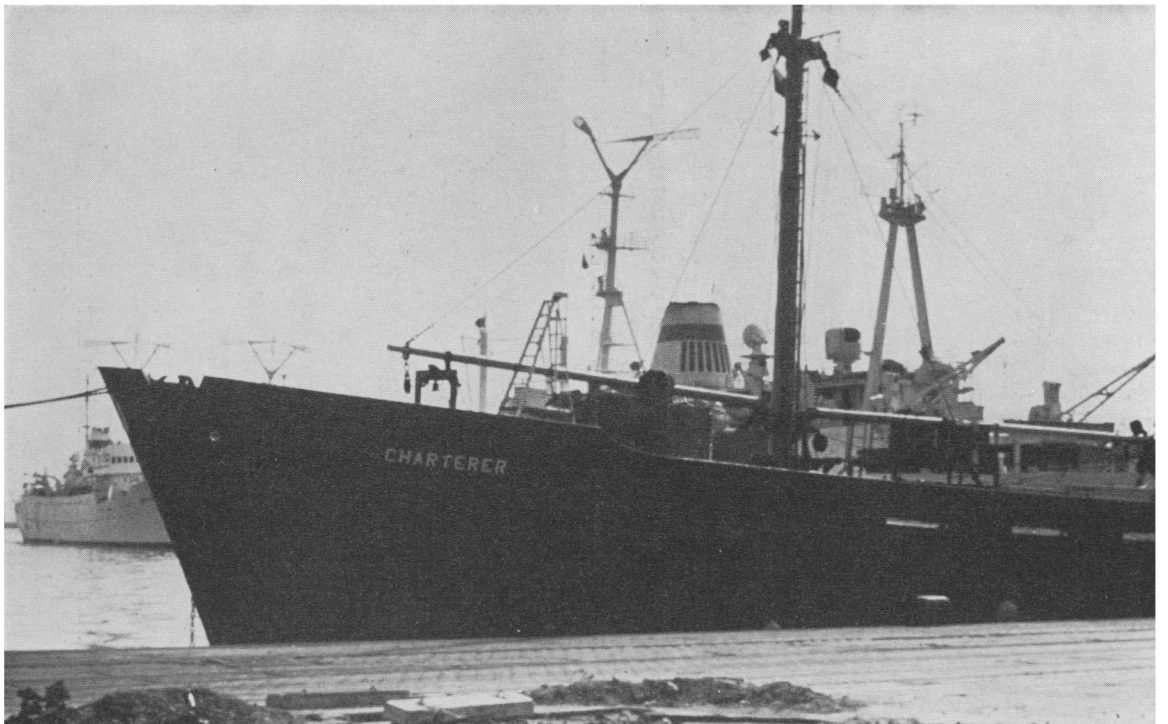

PLATE III—m.v. *Charterer* AT ANCHOR AT DAKAR

Soviet oceanographic ships are visible in the background. (See page 284.)

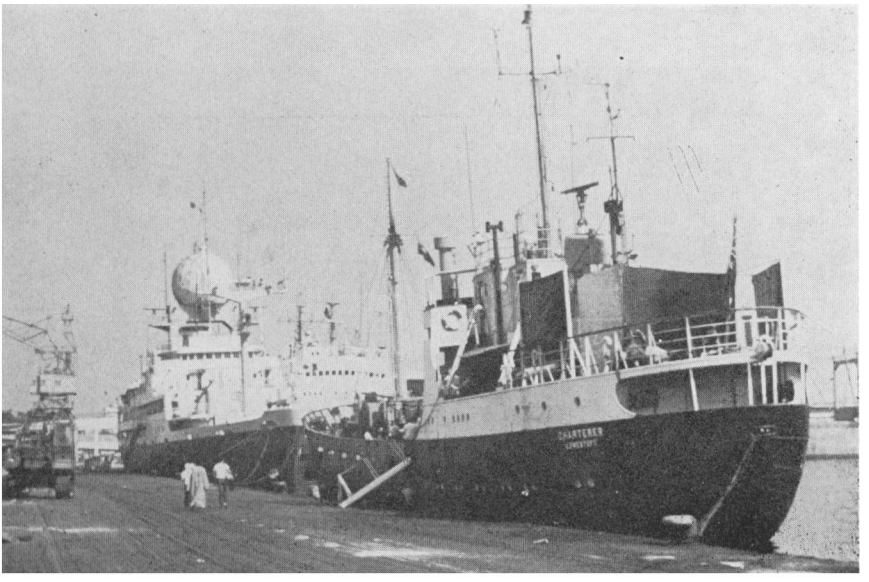

PLATE IV—m.v. *Charterer* (FOREGROUND) AND THE CANADIAN RESEARCH VESSEL *Quadra*

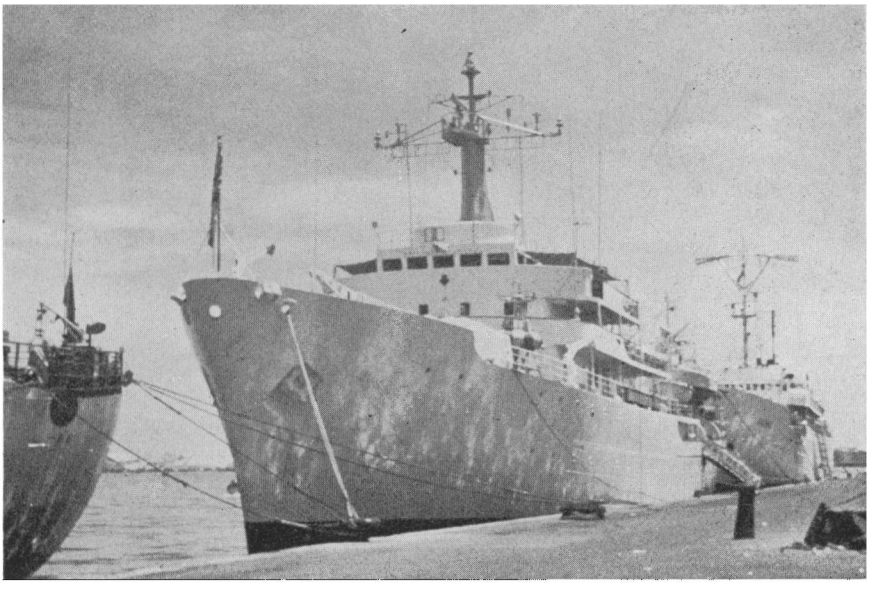

PLATE V—H.M.S. *Hecla* AT DAKAR WITH A SOVIET SHIP IN THE BACKGROUND
(See page 272.)

During the forecast, at 23°W and south of 7°N, an inversion forms below level $\sigma = 0{\cdot}718$ owing to warming at that level and cooling at $\sigma = 0{\cdot}844$. This is not an unrealistic structure and is often observed over tropical oceans in areas where there are few disturbances. A vertical cross-section of time-meaned observed and subjectively analysed temperatures along 23°W has also been constructed for comparison with the analysed and forecast structures (Figure 5 (*c*)), and this clearly shows an inversion between 900 and 700 mb. It seems that this feature, the warm surface layer and the probably spurious detail in the observed middle and upper troposphere are smoothed out in the analysis and interpolation to σ-levels. The forecast re-creates the inversion and also the warm layer near the ocean surface. The large negative departures of the observed temperatures near 100 mb from the model's 7°N average are at the tropopause which cannot be represented in this detail with the model's layered structure. A general cooling of about 1 K in the middle troposphere of the initialized field relative to the observed can probably be explained by a correction for estimated ship sonde error of about −0·5 K and the cooling evident in the 24-hour forecasts (Figure 5 (b)) which were used as background for the analysis. This forecast cooling appears to be due to insufficient compensation of radiative cooling by convective heating.

Cross-sections for relative humidity (not shown) suggest that the model had a tendency to make the air too moist. The form of convective parameterization used apparently required the whole grid square to be too near saturation before giving precipitation; this may partly account for the rather low values of predicted rainfall north of 10°N (Figure 3).

REFERENCES

BURPEE, R. W. 1974 Characteristics of North African easterly waves during the summers of 1968 and 1969. *J Atmos Sci*, **31**, pp. 1556–1570.

CARLSON, T. N. 1969 Synoptic histories of three African disturbances that developed into Atlantic hurricanes. *Mon Weath Rev*, **97**, pp. 256–276.

CLARKE, R. H. 1970 Recommended methods for the treatment of the boundary layer in numerical models. *Australian Met Mag*, **18**, pp. 51–71.

CORBY, G. A., GILCHRIST, A. and NEWSON, R. L. 1972 A general circulation model of the atmosphere suitable for long-period integrations. *Q J R Met Soc*, **98**, 809–832.

FRANCIS, P. E. 1975 The use of a multipoint filter as a dissipative mechanism in a numerical model of the general circulation of the atmosphere. *Q J R Met Soc*, **101**, pp. 567–582.

KESEL, P. G. and WINNINGHOFF, F. J. 1972 The Fleet Numerical Weather Central operational primitive-equation model. *Mon Weath Rev*, **100**, pp. 360–373.

MANABE, S. 1969 Climate and the ocean circulation: I. The atmospheric circulation and the hydrology of the earth's surface. *Mon Weath Rev*, **97**, pp. 739–774.

NITTA, T. 1969 Initialisation and analysis for the primitive equation model. Proceedings of the WMO/IUGG Symposium on Numerical Weather Prediction in Tokyo November 26–December 4, 1968. Japan Meteorological Agency, Tokyo, pp. VI-11–20.

SHAPIRO, R. 1971 The use of linear filtering as a parameterisation of atmospheric diffusion. *J. Atmos Sci*, **28**, pp. 523–531.

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METEOROLOGICAL OBSERVATIONS FROM H.M.S. 'HECLA' DURING THE FINAL PHASE OF GATE

By N. THOMPSON

(Meteorology Division, Chemical Defence Establishment, Porton Down)

SUMMARY

A description is given of tethered-balloon observations from H.M.S. *Hecla* during the third phase of GATE and of observations from an adjacent meteorological buoy. Some results obtained during the passage of a weak line-squall are discussed.

INTRODUCTION

An intensive study of the atmospheric boundary layer was made during the final phase of GATE by a number of well-equipped ships which took up positions in the C-scale array located within the B-scale polygon (Figure 1). Most of these ships were able to measure the low-level wind profile with fair accuracy, using pilot balloons tracked by stabilized radar or optically, and most also had tethered-balloon systems making multi-level measurements of wind, temperature and humidity, at heights up to about 1000 m. A number of ships also made surface observations with high time-resolution and accuracy, using sensors mounted on booms extended in front of the ships or on adjacent buoys.

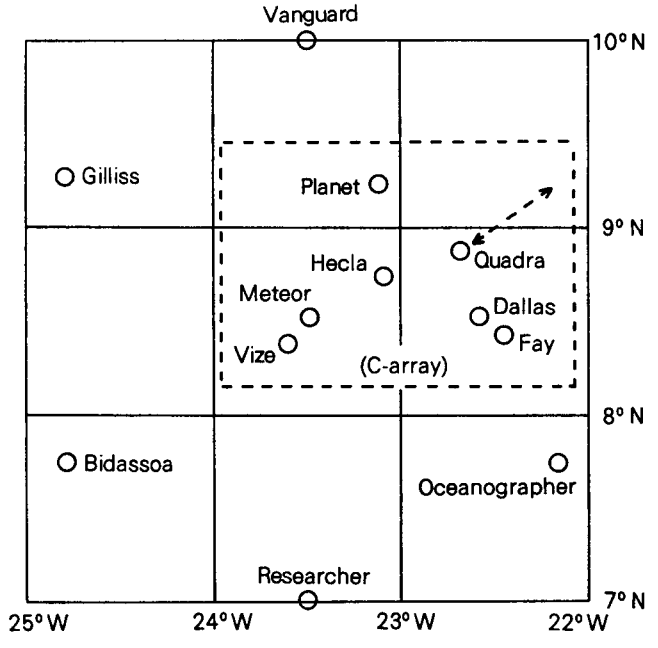

FIGURE 1—POSITIONS OF B- AND C-SCALE SHIPS IN PHASE III (30 AUGUST–19 SEPTEMBER 1974)

H.M.S. *Hecla* at the centre of the array carried teams from Imperial College and the Meteorological Office (Porton) who were concerned with a variety of boundary-layer observations. The contribution of the Imperial College group will not be discussed in this note; it included low-level windfinding using a very accurate stabilized radar system, radiosonde observations and all-sky cloud photography.

The main components of the program of the Porton team were the investigation of turbulence structures in the lowest few hundred metres of the atmosphere using a tethered-balloon system, and the measurement of near-surface parameters such as wind and temperature by a meteorological buoy (see Plate II). Balloon and buoy measurements had been made from the *Hecla* during the Joint Air–Sea Interaction Experiment (JASIN) in 1970 (Thompson, 1972) but the GATE equipment incorporated a considerable number of modifications. The remainder of this note describes the aims and experimental details of the program and gives a brief assessment of the results to date.

Tethered-balloon measurements

Previous experience had shown that the tethered-balloon system adopted would not allow multi-level measurements at heights up to much more than 400 m and the objectives of this program were necessarily restricted to the investigation of turbulence structure in the sub-cloud layer. Other constraints were the inability to fly in rain for long periods without damage to equipment or on occasions with adjacent lightning activity, or to obtain satisfactory data in very light winds. Within these limitations the program set out to acquire over as wide a range of conditions as possible multi-level data on wind velocity, temperature and humidity from which could be deduced, *inter alia*, the vertical fluxes of heat, moisture and momentum and the relation of these and other turbulence statistics to the large-scale flow fields and local cloud organization. Analysis of the results depends therefore on the use of cloud photographs, radiosonde data and, for example, divergence data.

The balloon (volume 80 m^3) was of conventional construction with air-filled fins; an air-filled compartment of variable volume under the helium cavity allowed compensation to some extent for expansion or contraction of gas due to temperature or height variations. After initial inflation on deck any further topping-up was through an umbilical cord about 20 m long which ran down the side of the tethering cable. The steel cable with a tensile strength of 1000 kg was paid out or recovered by a variable-speed electric winch on the forward end of the *Hecla*'s flight deck. Between the winch and snatch-block tether aft was an 'accumulator' consisting of fixed and movable pulleys whose spacing was controlled by a hydraulic ram; the cable was led round the pulleys and the stroke and speed of the ram were governed by a suitably integrated signal from a vertically stabilized accelerometer unit, thus compensating for motion of the tethering point of the cable (the snatch block aft) by continuously adjusting the amount of cable paid out beyond the accumulator. The balloon and tether were designed to survive winds of at least 25 m/s but were not put to this test since the maximum winds experienced were little more than 15 m/s.

The turbulence measurements were made with one or two instruments attached to the balloon cable at heights up to about 400 m. The measured parameters were magnitude of wind vector (miniature cup anemometer with horizontal rotor axis), inclination of airflow to the horizontal (hot wires mounted

on a pendulum), air temperature and wet-bulb depression (fine dry and wet platinum wires). Sensors were mounted on a light vane (Figure 2) that pivoted about the balloon cable; signal-conditioning circuits and transmitter were in a separate box attached independently to the cable below the vane. Signals were converted to audio frequencies and transmitted to the ship via 380-MHz links. Data were recorded on a multi-track analogue tape recorder in the ship's dry laboratory and then monitored 'off tape' and displayed on an ultra-violet recorder after de-multiplexing. Inclinometer and temperature circuits were calibrated before each run by substitution of dummy sensors (resistances). Variable offset resistances were incorporated in the airborne system in order to achieve maximum resolution in the temperature measurements: typical full-scale ranges were ± 2 deg. The expected accuracy was about $\pm 0{\cdot}2$ deg for wet- and dry-bulb temperatures and 5 per cent for inclination and wind speed. Rechargeable batteries used in the airborne system allowed runs of about 10 hours' length before battery changes were required.

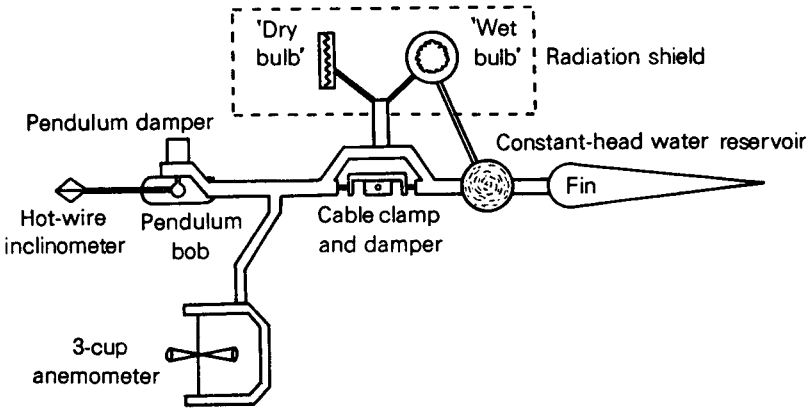

FIGURE 2—PLAN VIEW OF TURBULENCE SENSORS MOUNTED ON VANE

Overall length of vane is 0·7 m.

The balloon was inflated on 29 August but was found to lose its symmetry whenever not highly inflated (for example when the helium contracted in the evening owing to radiational cooling) and this resulted in rather unstable flying characteristics. After an early incident in which the balloon was driven to near the surface in a squall the gas was transferred on 31 August to another balloon which performed satisfactorily for the remainder of the experiment. Mechanical damage was caused to the instruments on two occasions by violent turbulence near the ship when being hauled down and on another occasion by a ship's power failure which caused a severe snatch in the cable accumulator and large downward acceleration of the cable. The accumulator system was out of action for maintenance for about 15 per cent of the time but otherwise performed satisfactorily and produced a significant reduction in sensor movement caused by ship's motion. There were occasional breakages of the fragile sensors and some electronic faults but sufficient replacements were carried to avoid all but temporary suspension of the measurement programs.

Apart from occasions with very light wind or heavy rain and lightning activity the most serious curtailment of the program was caused by adjacent low-flying aircraft. Aircraft missions were flown in the C-scale area on many days and since the *Hecla* had no aircraft navigation aid such as DME (Distance Measuring Equipment) the result was that the balloon had to be hauled down to about 50 m (too low to make measurements) on nearly all these occasions. On a few occasions with good weather conditions the balloon was allowed to be raised after an hour or so with aircraft in the vicinity but on nearly half the days there was a break of about six hours due to aircraft activities.

Two hundred hours of data were obtained, mostly with two heights of measurement. Meteorological conditions sampled ranged from highly suppressed (dry) convection to weak line-squalls with heavy rain and while some of the data suffered from instrumental faults it is expected that most will produce useful results. However, the analysis has been complicated by the fact that the *Hecla* was not anchored during GATE and made numerous changes of speed and course, often in association with its oceanographic (STD) program. This introduced difficulties in spectral analysis of the tethered-balloon data and makes it necessary to correct wind-speed data with the help of 1-minute values of heading and speed printed out by the ship's computer.

Buoy measurements

In strong sunshine (or at night with clear skies) and relatively light winds it is difficult to make representative temperature measurements from a ship with conventionally mounted instruments and at all times the corresponding wind measurements suffer from the ship's influence on the airflow. A meteorological buoy was used in an attempt to overcome these difficulties. The basic structure was a toroid of diameter 2·5 m with a lattice superstructure. The buoy was anchored in about 4700 m of water, 300 m of anti-fish-bite wire with braided nylon below being used. Wind speed was measured by a small reed-switch cup anemometer with built-in ratemeter giving a voltage output proportional to wind speed. The wind vane was a self-referencing type with built-in compass, and produced a single voltage output proportional to direction. Temperature sensors were platinum resistance thermometers connected to Wheatstone bridges and measuring air temperature, wet-bulb depression and sea–air temperature difference. The sea thermometer was at a depth of 1 m and other sensors were mounted at a height of 2 m on the upwind side of the superstructure. The air thermometers were mechanically ventilated inside a tubular radiation shield. The pressure sensor was a KDG aneroid connected to a Meteorological Office static head mounted near the other sensors. A large fin was used to orientate the buoy into wind. Data were recorded on a Rapco digital logger at 5-minute intervals and on a Plessey Logger at half this rate. Timing pulses for both systems came from the Rapco clock.

The buoy was visited on most days for washing the wet-bulb thermometer, changing batteries and checking on logger operation, and appeared to perform satisfactorily for about the first half of the measurement program, apart from intermittent operation of the thermometer aspirator (a fault eventually rectified). The timing system then failed following breakdown of the Rapco logger but logging restarted after a break of about three days, using a ¼-hourly mechanical timer in the Plessey Logger. On replaying the data tape it was found that both

the wet-bulb depression and air–sea temperature-difference signals had failed at the time when the buoy was launched, apparently because of damage to electrical cables caused by the launch. Fortunately the quantities which were to be derived from them (specific humidity and sea temperature) are those which can be obtained with fair accuracy from a ship by using an Assman psychrometer and bucket thermometer (both of which were used on board the *Hecla*). (See Plate II.)

Other measurements

Net all-wave radiometers (Kew-pattern ventilated fluxplates) were mounted on booms extending 6 m beyond the ship's sides to port and starboard. Outputs were logged on a potentiometric recorder. A static-pressure head (Meteorological Office pattern) was mounted on a boom to starboard of the mainmast and connected to two precision aneroid barometers mounted close to sea level in the gyroscope room. A small anemometer and wind vane were placed by the side of the static head and connected to the potentiometric recorder; the data were used in conjunction with the computer log of ship heading and speed to derive 1-minute values of wind velocity.

Intercomparisons

The buoy was lifted on 16 September and the *Hecla* then steamed to a position close to the *Meteor* in order to intercompare all upper-air and surface systems. The buoy was relaunched and tethered to the *Meteor*'s buoy for a period of about 15 hours. Both ships flew their tethered balloons for several hours with instruments at heights of 200 and 400 m. Low-level windfindings were compared by simultaneous radar tracking from both ships of pilot balloons. Standard meteorological observations were carried out at quarter-hourly intervals. The *Hecla* returned to station on 17 September.

Data processing

The tethered-balloon data were digitized at 10 Hz at Porton and then converted to horizontal and vertical wind speed, temperature and specific humidity, and transcribed to archive tapes using the Bracknell 360/195 computer. These archive tapes form the basic data set from which all results will be obtained. At present this data set is being used to produce various mean values and derived quantities such as standard deviations and covariances which are required by the World Data Centres in Russia and the USA, and the GATE Boundary Layer Sub-program Data Centre in Hamburg: vertical fluxes of heat, water vapour and momentum are also being calculated, and by the time this note is published it is expected that spectra and cospectra of the four parameters calculated at each height will have been produced from some of the data.

Other data such as those from the buoy are punched on cards and then archived on tape at Bracknell prior to international exchange.

Discussion

An extended discussion is inappropriate at present (July 1975) because of the considerable amount of data processing needed before the final results can be

obtained. First results are very encouraging and demonstrate that our participation in GATE was a success. To conclude this note and in order to indicate the sort of data obtained by the balloon system a brief description is given below of observations made before and during the passage of a weak line-squall.

On 13 September there was widespread moderate convection with a fair number of showers falling from large cumulus, and also some much larger cumulonimbus. The amount of convection suggested that the average low-level flow over the area was convergent. The general surface flow was south-westerly, about 8 m/s, and the upper flow which was approximately easterly was bringing over the ship anvils from thunderstorms some 30 km away to the east. After about 0900 GMT one of the larger cumulus clouds on the starboard forward quarter began to develop quickly vertically and then laterally and soon there was a line of showers orientated roughly north–south associated with it. The line then approached the ship, intensifying and deepening to become an obvious line-squall. The main rain areas passed on either side of the ship but the precipitation there was still fairly heavy during a period of about 20 minutes starting at about 1041. The rain lasted about an hour in all. The tethered-balloon system was flying with instruments at heights of approximately 96 m and 280 m while the squall developed and measurements were continued until shortly after 1100 GMT when a haul-down was necessary because of an impending aircraft mission.

Parameters derived from the tethered-balloon data for the period from 1000 GMT to the end of recording are plotted in Figure 3. Winds were around 9 m/s initially with a small increase with height. At the upper level the speed increased steadily after 1020 GMT until the squall reached the ship but at the lower height this increase was delayed until about 1030. Before the squall's arrival temperature fluctuations were small at both levels, probably because of the small air–sea temperature difference ($\approx 0{\cdot}5$ deg), but at the lower level in particular the variations of specific humidity were more marked. Vertical velocity fluctuations were very small at 280 m but much more pronounced nearer the surface where they are seen to be well correlated with fluctuations of water vapour.

The data were used to obtain vertical fluxes of sensible and latent heat by eddy correlation over the period 1000–1036 GMT and the results are plotted against height in Figure 4. The surface estimates were obtained by using bulk aerodynamic relations with values for the transfer coefficients for sensible and latent heat of 2×10^{-3} and $1{\cdot}3 \times 10^{-3}$ respectively (Muller-Glewe and Hinzpeter, 1975; Dunckel *et alii*, 1974).

The striking feature of the Figure is the strong convergence of the water-vapour flux. It is possible that the shortness of the length of record used has resulted in the loss of significant low-frequency contributions to the fluxes at the upper levels (the lowest resolved frequency was about 10^{-3} Hz) but the convergence is probably genuine in view of the small fluctuations of vertical velocity at the upper level: if unchanged it would lead to near-saturation in the layer up to 280 m in a few hours. In fair-weather trade-wind conditions it has been found (e.g. Donelan and Miyake, 1973) that the rate of decrease with height of the water-vapour flux is small and the present results suggest therefore that the boundary-layer structure was being or had been modified considerably by large convective systems in the vicinity.

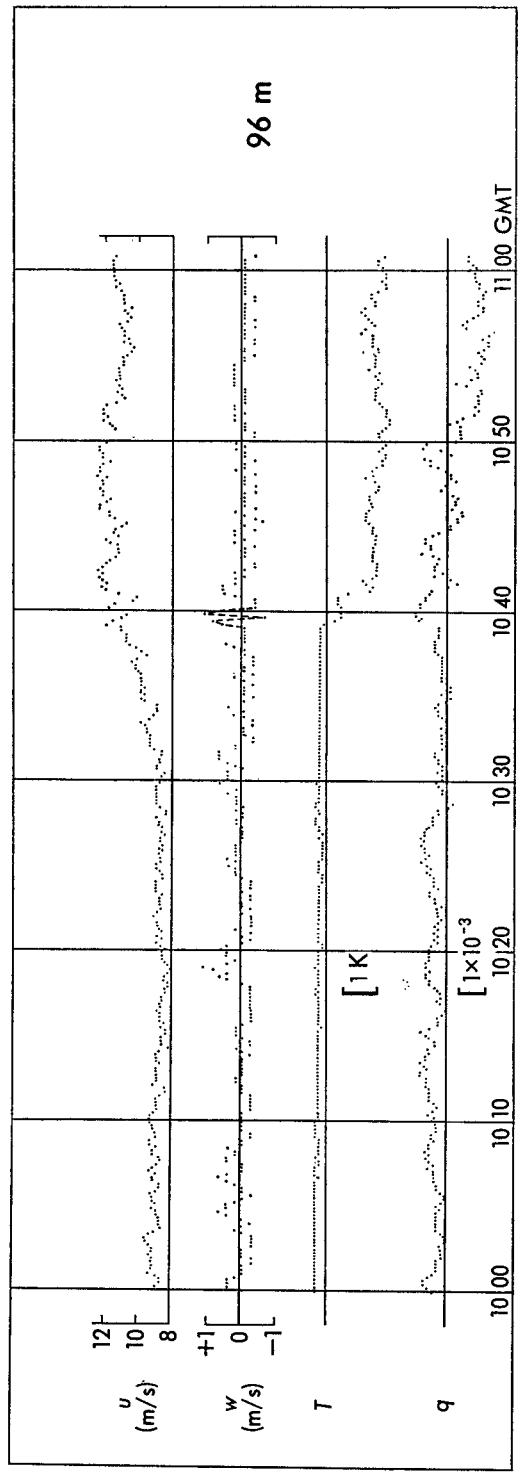

FIGURE 3—VARIATIONS OF WIND, AIR TEMPERATURE AND SPECIFIC HUMIDITY RECORDED ON 13 SEPTEMBER 1974 AT A HEIGHT OF 96 METRES

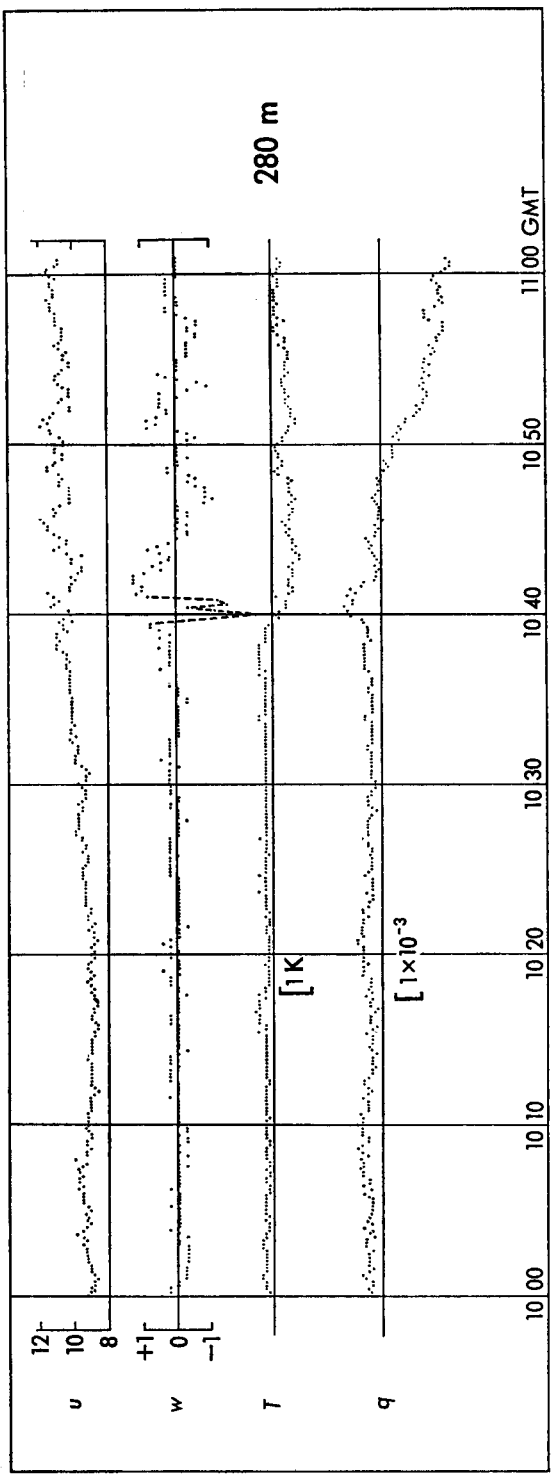

FIGURE 3 *continued*—VARIATIONS OF WIND, AIR TEMPERATURE AND SPECIFIC HUMIDITY RECORDED ON 13 SEPTEMBER 1974 AT A HEIGHT OF 280 METRES

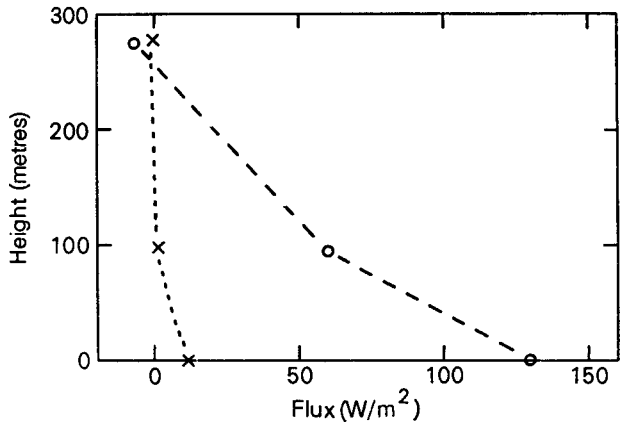

FIGURE 4—VERTICAL HEAT FLUXES 1000–1036 GMT, 13 SEPTEMBER 1974

x - - - x Sensible heat o – – o Latent heat

The surface wind backed slightly (from 225° to 210°) a few minutes before arrival of the squall, began to increase significantly after about 1037 GMT, and veered temporarily to 270° and increased further just before the start of the rain. The line was orientated roughly from 020° to 200° and the wind component perpendicular to the line increased from about 2 m/s to 7 m/s during its passage between 1038 and 1041 GMT. Successive radar pictures suggested a speed of propagation of about 5 m/s (or 900 m in 3 minutes) and the corresponding divergence was therefore about -5×10^{-3}. It was not possible to calculate divergence from the tethered-balloon measurements in the absence of wind-direction data, but at 280 m the divergence was almost certainly numerically smaller than that at the surface because of the smaller change of wind speed on passage of the squall. After about 1110 GMT the surface wind had decreased to near 8 m/s, little different from its value before the arrival of the squall.

The squall's arrival was marked by a rapid fall of temperature at the surface and the two tethered-balloon levels (Figure 3) and a brief increase in specific humidity. The air then became drier and by 1100 the specific humidity at 280 m was about 3×10^{-3} lower than initially, with about half this decrease at 96 m but little change at the surface. The largest fall of temperature was at the surface, about 2·5 K, with the least change at 280 m. The vertical-velocity fluctuations became considerably larger at the upper level when the squall arrived and on average there were updraughts at both heights for a few minutes after temperatures began to decrease but later the average motion was downward. The differential fall of temperature produced a strongly stable layer away from the surface, especially between 96 m and 280 m and this seems to have inhibited vertical-velocity fluctuations at the lower of these two levels but at 300 m where the stability changes may have been smaller the level of turbulence remained high.

Both tethered-balloon levels experienced a double downdraught superimposed on the generally rising motion in the squall-line's vicinity. The downdraughts were delayed by about 25 seconds at the upper level and allowing for the angle of the balloon cable this implies a backward slope of the undercutting cold air of around 10 degrees, but this value is very sensitive to the

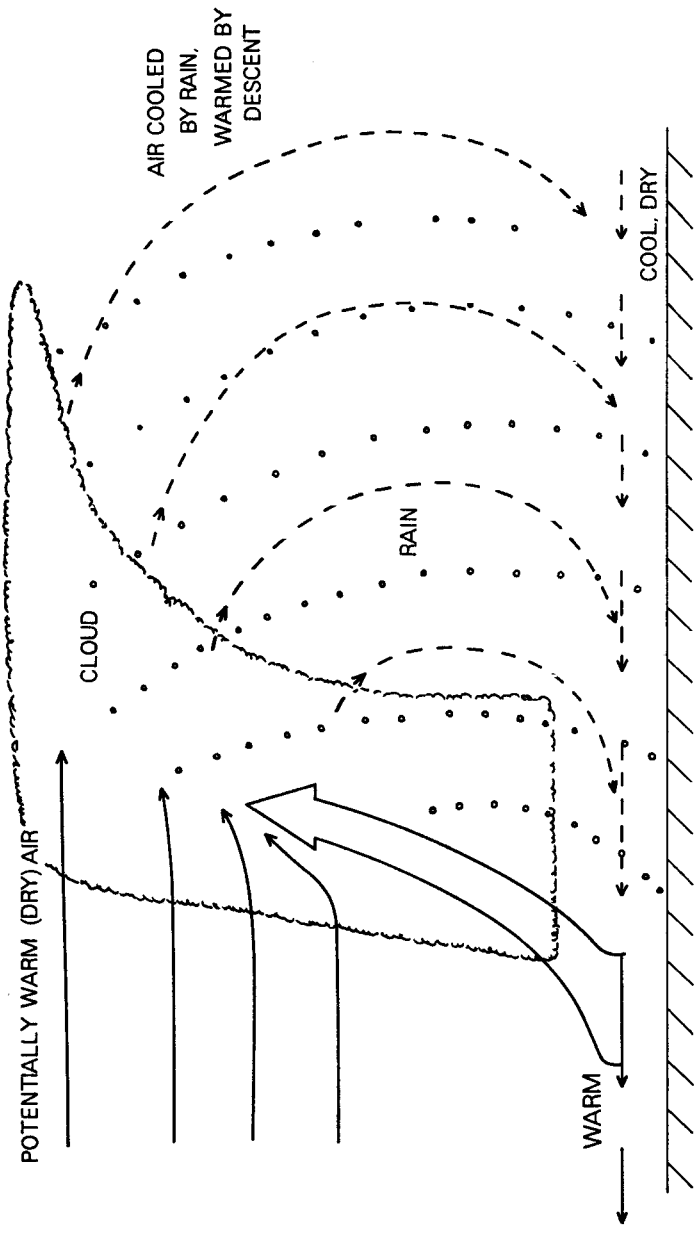

FIGURE 5—SIMPLIFIED CROSS-SECTION OF LINE-SQUALL

speed of travel of the squall which was known only approximately. The mean upward velocity at the upper level over the period from 1038 to 1046 GMT was 0·25 m/s and at the lower level (1038–1042) 0·15 m/s. Assuming that the divergence was close to zero apart from a 3-minute period centred close to 1040, and that it was constant with height, the calculated vertical velocities are 0·7 and 0·4 m/s respectively. If the divergence decreased linearly to zero at 280 m the calculated values become 0·35 and 0·3 m/s, still significant overestimates.

In general the data support the classical picture of the line-squall maintaining itself through wind shear and evaporative cooling (Figure 5). Air behind and within the squall must have been cooled by evaporation of rain into it and since even then it is drier than the air originally at the same height it must therefore have originated at higher levels. There are no representative radiosonde data for the period from which the temperature and humidity data above the surface can be deduced (a sonde was released from the *Hecla* at 1102 GMT but this ascended through the main rain area) so it is not possible to draw any firm conclusions about the level from which the dry air at 280 m originated. However, rough calculations based on the average of radiosonde ascents made from Russian ships in the A/B array in Phase III (Antsipovich *et alii*, 1975) suggest that the air descended from a level near 1500 m if it is assumed that insignificant mixing with air at lower levels took place. The vertical wind shear separated the updraught and downdraught regions and allowed the latter to develop over a wide area. The surface fluxes were estimated from the ship's surface data by using the bulk aerodynamic formulae. The sensible heat flux increased by a factor of about 8 on arrival of the squall, and the Bowen ratio changed from 0·08 to 0·5, with a doubling of the total heat flux (sensible plus latent heat) to about 290 W/m^2. The squall therefore appears to be a successful mechanism for producing enhanced vertical transfers, first by removing moist lower-boundary-layer air from an area of some tens of square kilometres, pumping it upwards and replacing it with dry air, and secondly by enhancing the surface fluxes themselves.

ACKNOWLEDGEMENTS

The use of the facilities provided by H.M.S. *Hecla* was by permission of the Hydrographer of the Navy. Many others gave assistance and advice, particularly the ship's company of the *Hecla*, Lt Cdr T. McAndrew, and D. Winters, D. R. Davies and J. Whitlock, who took part in GATE and were involved in many aspects of instrumentation and data processing.

REFERENCES

ANTSIPOVICH, V. A. *et alii* 1975 On the orders of the values of the meteorological elements obtained in the A/B array in the period of GATE. GATE Report No. 14, Vol. II, World Meteorological Organization, Geneva and International Council of Scientific Unions, pp. 233–244.

DONELAN, M. and MIYAKE, M. 1973 Spectra and fluxes in the boundary layer of the trade-wind zone. *J Atmos Sci*, 30, pp. 444–464.

DUNCKEL, M. *et alii* 1974 Turbulent fluxes of momentum, heat and water vapour in the atmospheric boundary layer at sea during ATEX. *Boundary-layer Meteorology*, 6, pp. 81–106.

MULLER-GLEWE, J. and HINZPETER, H. 1975 Turbulent fluxes in the ITCZ during GATE Phase III at Station 27. GATE Report No. 14, Vol. I, pp. 224–232.

THOMPSON, N. 1972 Turbulence measurements over the sea by a tethered balloon technique. *Q J R Met Soc*, 98, pp. 745–762.

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THE METEOROLOGICAL OFFICE CONTRIBUTION TO THE SHIPBORNE OPERATION OF GATE

By P. H. JEFFRIES

(Lerwick Observatory)

SUMMARY

The ships chartered by the Meteorological Office as part of the UK contribution to GATE are described together with an account of the instruments carried and observations made; these included wind, pressure, sea temperature, radiation, rainfall, and six-hourly upper-air soundings. Aerosol sampling was also carried out as part of an investigation into the transport of Saharan dust. Some practical difficulties are described and a summary given of the results obtained.

INTRODUCTION

GATE (GARP Atlantic Tropical Experiment) took place during the summer of 1974. It was a unique, major international operation planned to examine the many factors which control the interaction of sea and air over the tropical North Atlantic. It is the redistribution of the excess solar energy received in the tropics towards the polar regions which produces the weather systems of the middle latitudes. An appropriately detailed knowledge of the tropical atmosphere is, therefore, a prerequisite to a better understanding of the massive heat engine which is the earth's atmosphere.

The Experiment took place in three phases broadly covering July, August and September. This is the time when solar heating is at its maximum, the Intertropical Convergence Zone (the ITCZ) has moved northwards following the sun, and certain recognizable features show their maximum frequency. One of these recurring features, known as a cloud cluster, has been revealed during satellite surveillance of the tropics. Such clusters are typically about 100 kilometres in diameter. During their passage westwards across the Atlantic they sometimes disperse or, at the other extreme, develop into the hurricanes which are features of the west Atlantic and Caribbean Sea.

To examine the processes in detail throughout the GATE area (20°N to 10°S and 40°E to 70°W) was impossible. In planning the Experiment, interest was concentrated in an area most likely to be affected by cloud clusters. The atmospheric processes investigated were on three scales; the C-scale for features of the order of 1 km to 10 km, the B-scale for features of the order of 10 km to 100 km and the A-scale for those of 100 km to 1000 km. The ships, which were allocated by the various countries to the Experiment, were divided according to their individual capabilities for monitoring the physical processes on one or more of these scales. Ships ranged from oceanographic research vessels with radar and, perhaps, the capability of flying a tethered balloon and deploying buoys (and so possessing the sophistication of equipment necessary to examine the fine C-scale structure of the atmosphere), to ships with the relatively simpler instrumentation suitable for measurement on the A-scale. The latter were distributed round the inner core of C-scale ships at 08° 30'N, 23° 30'W, and across the Atlantic, to monitor the passage of synoptic-scale features through the GATE area.

The United Kingdom A-scale ships

The two sister ships chartered by the Meteorological Office as part of the UK contribution were based at Lowestoft. Their tonnage of 477 tons made them amongst the smallest ships taking part. The *Charterer* and *Endurer* of Gardline Shipping Ltd sailed from Lowestoft in early June fully equipped to undertake the main requirements of A-scale ships. Scientific stores for the whole three-month period were carried. These included 180 cylinders of helium with which the balloons used for the upper-air ascents were filled, the balloons themselves, and the many ancillary stores required. In addition, the holds of the ships had been modified to hold extra fresh-water tanks and a deep-freeze capacity which was to make them virtually self-sufficient in most food items for the entire period. The working space for the equipment and staff was in the stern one-third of the ship and measured some 6 metres by 2½ metres. Six scientific staff were carried and one technician. In addition, since one of the requirements was for data to be disseminated in real time, two radio operators were provided to transmit all meteorological data to the communications ships. These latter, with their more powerful transmitters, collected and retransmitted the data from several ships to the GATE Operations Centre at Dakar. (See Plates III and IV.)

Instrumentation and observations

Both UK ships were required to make a surface observation every hour throughout the time they were in the GATE area. Each ship was provided for this purpose with instruments which had been well tried on ocean weather ships. A standard cup and vane Mk IV anemometer was mounted on the cross-tree of the mainmast, with readings displayed on dials in the office. Pressure was measured with precision aneroid barometers. Perhaps uniquely among the ships taking part, we also had a static pressure head mounted on the cross-tree and connected to the precision aneroids; this reduced to a large extent pressure fluctuations which might otherwise have occurred in aneroids mounted in the closed interior of a ship. Sea temperatures were sampled with a canvas bucket and thermometer. In addition, we used an infra-red thermometer. This instrument, which was hand-held, gave the temperature of an object at which it was pointed as a reading on a dial. Calibration before use was a simple operation involving the exposure of the instrument to a 'black-body' maintained at a constant temperature. Strictly this instrument gave the 'sea-skin' temperature. These readings, in conjunction with knowledge of the global incoming short-wave and long-wave radiation, may allow a reasonable estimate of radiation balance to be made.

Air temperature was measured by using mercury-in-glass thermometers in standard marine screens exposed on both bridge wings. Readings from these were supplemented by additional ones from electrical resistance thermometers (ERTs). The ERT readings were recorded once a minute on the chart of a 'Kent' recorder.

A rain-gauge was also carried. The collecting funnel was mounted on the cross-tree and any rain collected was passed down a plastic tube to the bridge where it activated a peristaltic pump; each action of the pump was registered as an 'event' on magnetic tape which also bore one-minute time marks. A crude magnetic-tape record of both rate and duration of rainfall was thus

obtained. A cumulative total of rainfall events was also registered by an electromagnetic counter. Rainfall was measured every six hours while the ships were occupying their nominal positions. Expendable bathythermographs were used to measure sea temperatures to a depth of 400 metres. The results of these soundings were recorded on a strip chart. One sounding a day was made during Phases I and II but this was increased to eight a day during Phase III. Additionally, while the ships were *en route* to and from assigned positions, soundings were made at intervals of approximately 60 nautical miles. The results of one of the soundings made in a day were transmitted to Dakar.

Upper-air soundings were normally made four times a day at 00, 06, 12 and 18 GMT. A reduced program of two soundings a day was made during passage to and from our positions. These were all reported to Dakar as soon as the ascent had been computed and encoded. The soundings gave temperature, pressure and humidity with wind data, to an average height of 20 kilometres. The equipment used for these soundings was new and its greatest asset was that winds could be measured without the necessity of installing on the ships a stabilized radar—a prohibitively expensive operation. Winds were determined by using standard navigational radio methods (Navaid) to measure the small displacements of the radiosonde transmitter. In our case, and for the GATE area generally, the equipment was designed to use either VLF navigational signals or Omega signals. The accuracy of the system depended on its being able to receive reliably the signals from three stations appropriately located. This was not always possible. Because hand computation of winds took an unduly long time, the equipment contained a small computer. Ships of other nations also used this equipment and so there was a measure of uniformity which is not always possible to achieve in an international operation.

Global incoming short-wave and long-wave radiation was also recorded. A good exposure of the instruments used for these measurements was difficult to obtain. They were eventually mounted on top of the wheel-house although it was still possible for masts and aerials to cast shadows over the sensitive elements. However, with the ceaseless rolling of the ship, the average effect of these was small. The pyranometers were mounted in damped gimbals to reduce the effect of rolling and pitching. The outputs from the radiation instruments were continuously recorded on a potentiometric recorder.

A final experiment, in which both UK ships were involved, was on behalf of the University of Miami. This was an aerosol sampling program designed to determine how much and in what circumstances Saharan dust is carried across the North Atlantic to the Caribbean area where it has been detected. Again, a suitable exposure for the sampling equipment was difficult to find on such small ships but a reasonable compromise was effected in the end. The experiment was a simple one with a filter being changed once a day and photometer readings being taken from time to time.

Results and problems

The success of an individual A-scale ship contribution to GATE is difficult to assess until an analysis of its results against the whole field of observations is possible. This must take time, but the data are being processed to a tight schedule defined in the GATE plan. With such an ambitious program it was inevitable that some failures occurred. There are few ships which can claim

complete adherence to their schedule. The planned program was itself altered during the course of the Experiment to take account of unforeseen situations in the weather or to respond to some difficulty or failure among the ships. The UK ships had their share of troubles too. Recalcitrant generators giving unstable outputs (or on one occasion none at all), failing air conditioning, which entailed equipment (and people) working in temperatures for which they were not designed, and vibration, which we had anticipated to a certain extent, but which, in the end, took its slow, inevitable toll of the electromechanical parts of our instruments. Much was learnt in these respects which will be of value in the future. On the positive side, both UK ships made over two hundred upper-air ascents to an average height of over 20 kilometres. Some of these data were difficult to assess at the actual time, owing to uncertainties arising in the output from the computer. The post-Experiment analysis now being carried out will probably reveal more usable detailed data than was originally thought possible. One of the benefits of the system we used for upper-air ascents was that almost all the original data were stored on magnetic tape. It will be possible to re-examine these raw data and clarify those points of difficulty which occurred during the actual Experiment.

Surface observations at the required frequency were maintained throughout the time the ships were in the GATE area. Rainfall measurement, difficult enough at a land station, is likely to yield the least reliable of our data. The appreciable cooling in the surface sea temperature that was noted during heavy rain will raise interesting questions. Some 250 successful bathythermograph soundings were made by each ship. Radiation, both long-wave and short-wave, was successfully recorded during the Experiment. It had been hoped to log these data automatically on paper tape but this did not prove possible. The aerosol sampling program was completed to the satisfaction of the University of Miami. The scale of dust transport from the Sahara is difficult to visualize. During some of the more vigorous outbreaks the effects are very noticeable, with convection much suppressed, a marked diminution of incoming radiation and the sun reduced to a milky ball. On one occasion at 15°N 35°W the ship itself was covered in a fine red dust. It is hoped that with the increased number of data resulting from the GATE observations this phenomenon will be better understood.

Despite the difficulties, a reasonable degree of success was achieved. The A-scale ships, by the very nature of their responsibilities, worked independently. The data they collected and broadcast were used by the GATE Operations Centre to prepare the synoptic analyses used in the planning of the daily experiments involving aircraft, and those experiments requiring an enhanced observation program on the ships. They were also used by the special group at Bracknell for their 11-layer mathemetical model of the tropical atmosphere in as near to real time as communications allowed. These were the immediate and successful uses to which the data were put. But it is also in the longer term that the quality and usefulness of our data will be judged. The weather ranged from steady north-east trades in the north of the GATE area, to generally cloudy, disturbed conditions with torrential rain near the ITCZ further south. Within this general pattern were fluctuations that only careful scrutiny of the data will reveal.

Conclusion

Much has been said and written about meteorology being one of the few examples of genuine international co-operation. Never was this more fully demonstrated than by the example of GATE where experiences and difficulties, shared on a personal basis, must have made even more secure the foundations laid in previous years. The friendliness and help that we on the UK ships enjoyed during our in-port periods at Dakar provided a personal and immediate stimulus to the spirit of co-operation upon which the Experiment had been so successfully based.

International emblem of GATE

The design shown above, which has been printed on the covers of this and the previous issue of the *Meteorological Magazine*, is the international emblem of GATE and was used extensively in and around the main operations base at Dakar, Senegal. Beneath the compass points—indicated by their initial letters in French which is the official local language—there is a diagrammatic representation of a baobab tree, the national emblem of Senegal. 'E.T.G.A.' is the French version of 'GATE' and is formed from the initial letters of 'Expérience Tropicale GARP Atlantique'. The wreath or chaplet of leaves is the United Nations symbol as used in the official emblem of WMO.

The following announcement has been received from the GARP Activities Office of the World Meteorological Organization:

ANNOUNCEMENT OF THE GATE VISITING SCIENTIST PROGRAMME ADOPTED BY THE TROPICAL EXPERIMENT BOARD

(VIIIth Session, Geneva, 4–6 May 1976)

The success of an international experiment like GATE requires not only the exchange of data, but also an exchange of ideas, theories, and the practical details of instrument design and calibration. After the initial analyses of national data, nations can greatly benefit by arranging the exchange of scientists involved in GATE. Therefore, the Tropical Experiment Board (TEB) at its VIIIth session (Geneva, 4–6 May 1976) endorsed and adopted the 'GATE Visiting Scientist Programme'.

The Programme is an opportunity for scientists who are working on GATE-related problems (e.g. theory, numerical modelling or data analysis) to continue their work at an institution in another country. Although the Programme is orientated towards one of the five Sub-programme Data Centres, the opportunities are not limited to those institutions.

Scientists who are interested in this opportunity may contact their national GATE 'focal points' and the institution which they desire to visit. They should also write to the GARP Activities Office (GAO) and include a *curriculum vitae* or professional résumé, a summary of the proposed work or research project, the name of the desired institution and a proposal for the length of visit. The role of the GAO will be to bring the credentials of the individual to the attention of the institution quickly and to coordinate subsequent arrangements.

At the present time there are opportunities at the following institutions:

Canada:	Department of Physics, University of Toronto, Toronto.
France:	The Oceanographic Sub-programme Data Centre, Brest.
F.R.G.:	The Max-Planck Institute for Meteorology and the Meteorological Institute of Hamburg University, Hamburg.
U.K.:	Meteorological Office, Bracknell.
U.S.A.	Many Universities, Research Centres and U.S. Government Research Laboratories.
U.S.S.R.:	Hydrometeorological Research Centre, Moscow. Main Geophysical Observatory, Leningrad. State Oceanographic Institute, Moscow.

Financial support for these visits and exchanges (including travel and *per diem* payments) must be worked out on an individual basis. The selection of the individual will depend on the needs and interests of the host institution; the decision rests with the host alone.

LETTER TO THE EDITOR

An improved wind-direction indicator

Readers have pointed out that some of the statements in our recent paper (Moulsley, Fryer and Pike, 1976*) need some clarification, especially the sentence immediately following equation (10) on page 149. The Royal Aeronautical Society report cited gives graphs of normal force coefficient C_N (Figure 8) versus angle of incidence α for various values of b/c. Our equation (9) is an approximate algebraic representation of the slopes of the graphs as a function of b/c. Our choice of 20 for a value of b/c was arbitrary and not entirely justified from the limited range of values for the graphs but it is probably about the limit from practical considerations. Even with this optimistic value for b/c the conclusion is that the support rod needs to be quite long for critical damping to be achieved. We should have written '$dC_N/d\alpha$ = rate of change of normal force coefficient with angle' rather than '$dc/d\alpha$ = rate of change of lift coefficient with angle'. We apologize for this ambiguity but we believe the general argument to be valid as evidenced by the behaviour of the device in practice.

National Institute of Agricultural Engineering, L. J. MOULSLEY
Wrest Park,
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Bedford MK45 4HS.

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* MOULSLEY, L. J., FRYER, J. T. and PIKE, K. S.; An improved wind-direction indicator. *Met Mag*, 105, 1976, pp. 148–153.

REVIEW

Our changing climate, by John Gribbin. 150 mm × 210 mm, pp. 95, *illus.*, Faber and Faber, 3 Queen Square, London WC1N 3AU, 1975. Price: £2.75.

For very good reasons climatic change has become in recent years a very topical subject. But the pressing need to understand past changes and predict future ones does not automatically mean that instant solutions are now at hand. It is particularly regrettable to find a book which is aimed at young people giving this impression and conveying a very unbalanced account of this complex issue.

This book will certainly leave the reader with the impression that all changes of climate are due to changes in solar activity. Since the incoming solar radiation is the prime energy source for the earth's atmosphere this *seems* an eminently sensible conclusion. The author, however, does not spare a page in which to discuss the relation between the total energy coming from the sun and the sunspot number. While this relationship remains undetermined there is no secure physical basis for a relation between climate and sunspot number. The relation has to be established statistically with all the attendant dangers

of sampling and chance relations arising from averaging. In most cases significance tests show that the relationship between the climatic series, whether temperature, rainfall, pressure, or circulation strength, and the sunspot number could have arisen by chance. There are moreover unexplained changes in phase which should be a warning against making predictions based on a constant phase relationship. This low statistical significance means that even if the relationship is a real one it explains only a small part of the variability. It is therefore quite misleading to attribute the changes in climate entirely or mainly to variations in the number of sunspots as the author of this book has done.

There is no mention of the likelihood even of changes arising from internal effects, that is to say within the earth–sea–atmosphere system. Yet the heat stored in the oceans is so large that there could well be variations in the rate of transfer to the atmosphere capable of producing many of the climatic fluctuations. And there is not a word about the effect on climate of variations in global cloud cover, atmospheric carbon dioxide and water vapour, or the possible effect of changing turbidity due to dust—volcanic, natural and man-made. Yet careful studies have shown that all these effects must be at least considered in the attempt to explain past climatic changes.

The climatic forecast with which the book concludes emphasizes and crowns with a conical cap the author's lack of judgement in this book. Such a forecast is based entirely on the secular cycle in sunspot activity. The relation of climate to this is not securely established. If it is real it does not explain all the variability and it is foolish and unscientific to ignore all the other factors which could affect the outcome.

M. K. MILES

HONOUR

The following award to a recently retired member of the Meteorological Office was announced in the Queen's Birthday Honours List, 1976:

M.B.E.

Mr I. A. Nixon, who at the time of his retirement was a Higher Scientific Officer at Kirkwall Airport, Orkney.

AWARD

Award of IMO Prize to Academician Ye. K. Fedorov

We note with pleasure that the twenty-first International Meteorological Organization Prize for outstanding work in meteorology and in international collaboration has been awarded this year to Academician Yevgeny Konstantinovich Fedorov, formerly Head of the Hydrometeorological Service of the USSR and at present Director of the Institute of Applied Geophysics of the Academy of Sciences of the USSR.

OBITUARIES

It is with regret that we have to record the death on 30 May 1976 of Dr P. A. Einstein, Senior Scientific Officer, and the death on 23 June 1976 of Mr W. P. Moss, Photographer, both of Met O 16.

VOL. 105 NO. 1250 SEPTEMBER 1976

CONTENTS

Page

The United Kingdom Meteorological Office objective analysis scheme for GATE. D. E. Jones 249

Numerical modelling using GATE data. W. H. Lyne, P. R. Rowntree, C. Temperton and Julia M. Walker 261

Meteorological observations from H.M.S. 'Hecla' during the final phase of GATE. N. Thompson 272

The Meteorological Office contribution to the shipborne operation of GATE. P. H. Jeffries 283

International emblem of GATE 287

Announcement: GATE 'Visiting Scientist Programme' 288

Letter to the Editor 289

Review
Our changing climate. J. Gribbin. *M. K. Miles* 289

Honour 290

Award 290

Obituaries 291

NOTICES

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